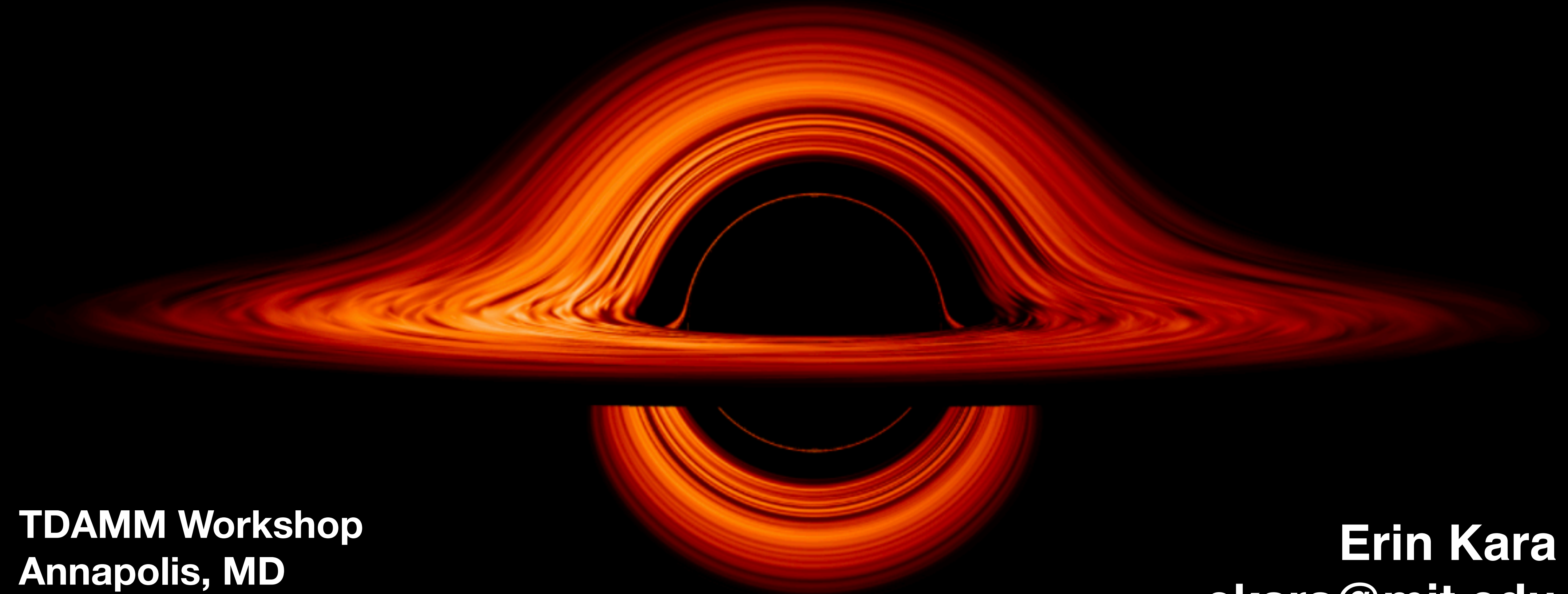


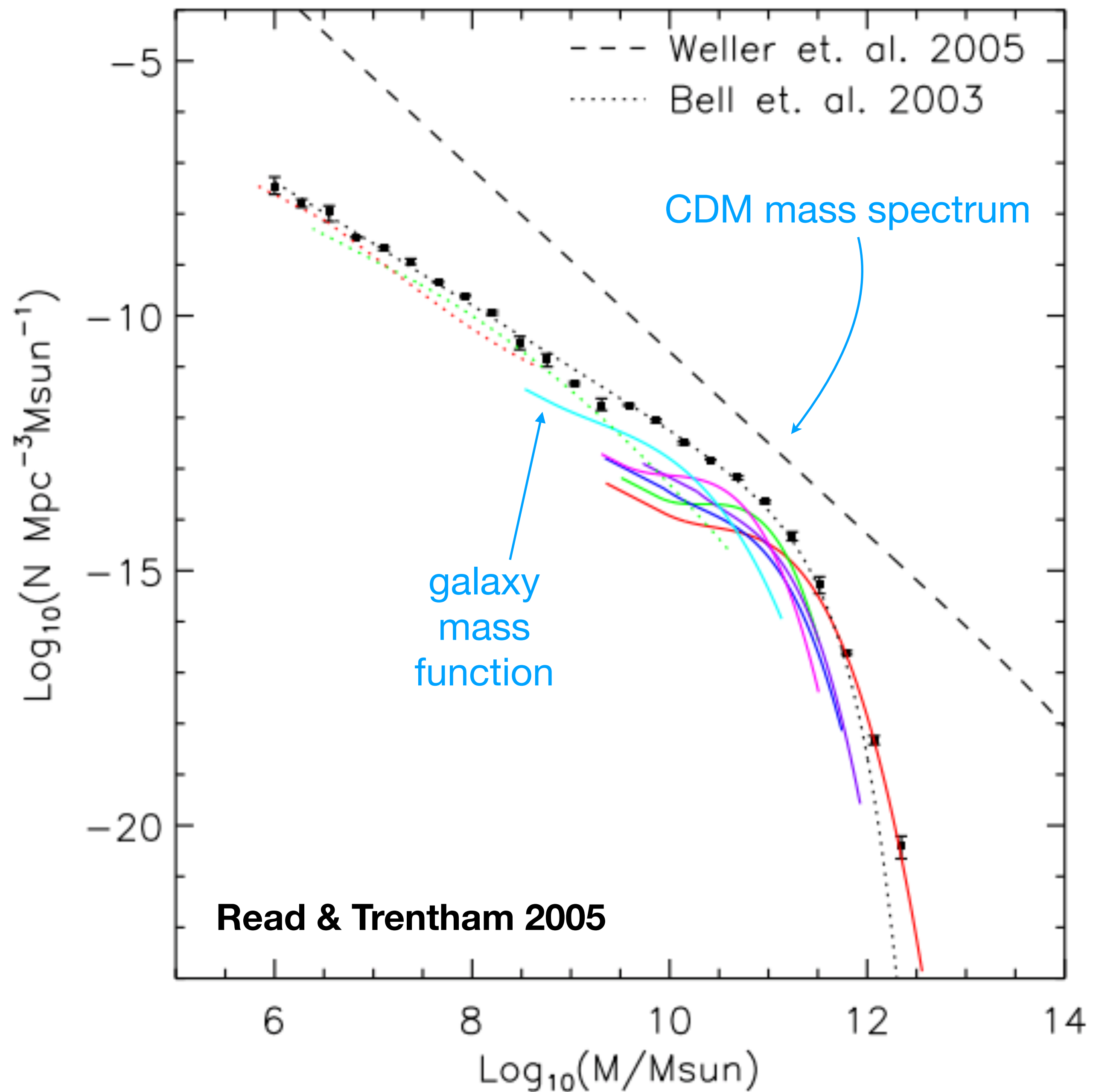
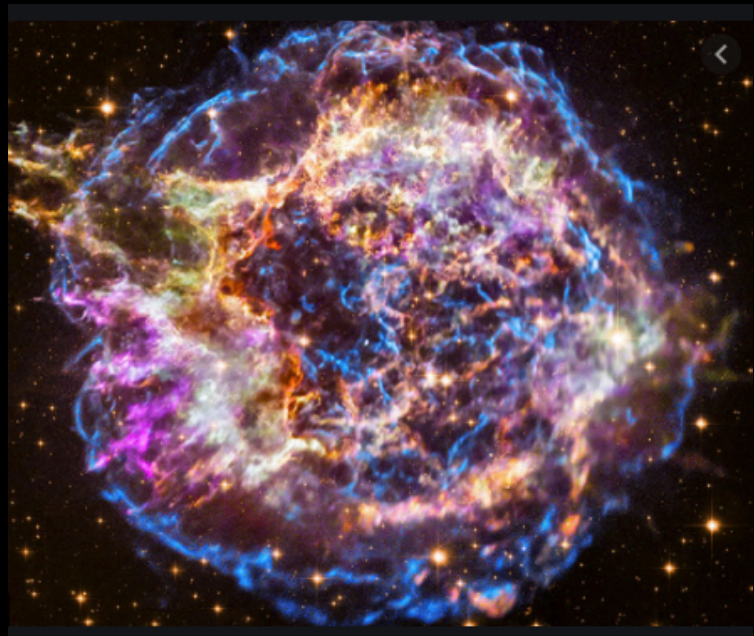
Black hole X-ray Binaries in the Multi-Messenger Era



TDAMM Workshop
Annapolis, MD
23 August 2022

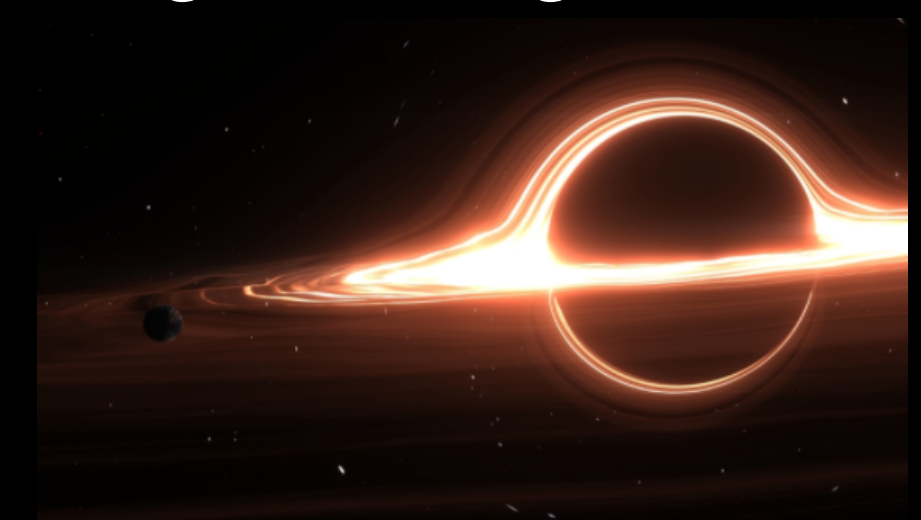
Erin Kara
ekara@mit.edu

Not enough
low mass galaxies



The role of
black holes in
galaxy
evolution

Not enough
high mass galaxies

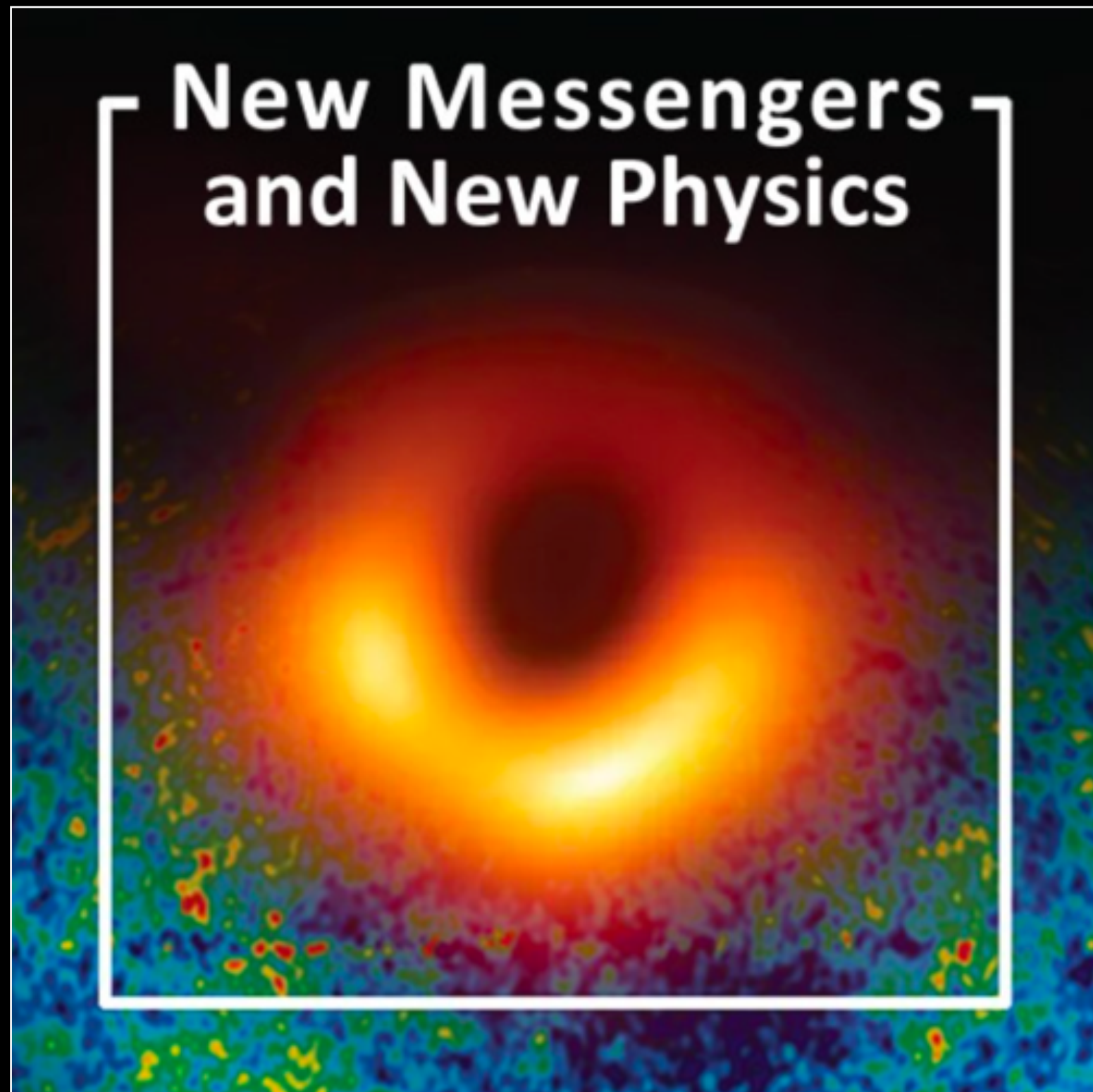


AGN Feedback through jets

How are they
powered?



Astro2020 asks:

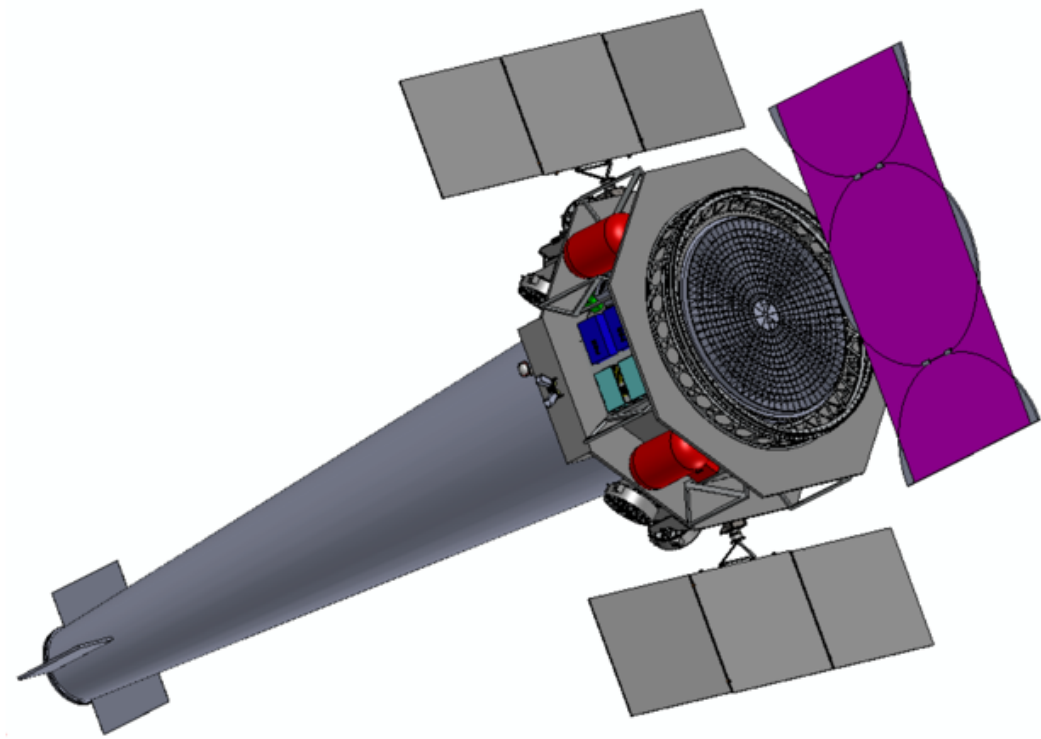


*B-Q2: “Why do some compact objects eject material in nearly **light-speed jets**, and what is that material made of?”*

*B-Q3**: “What **seeds supermassive black holes**, and how do they grow?”*

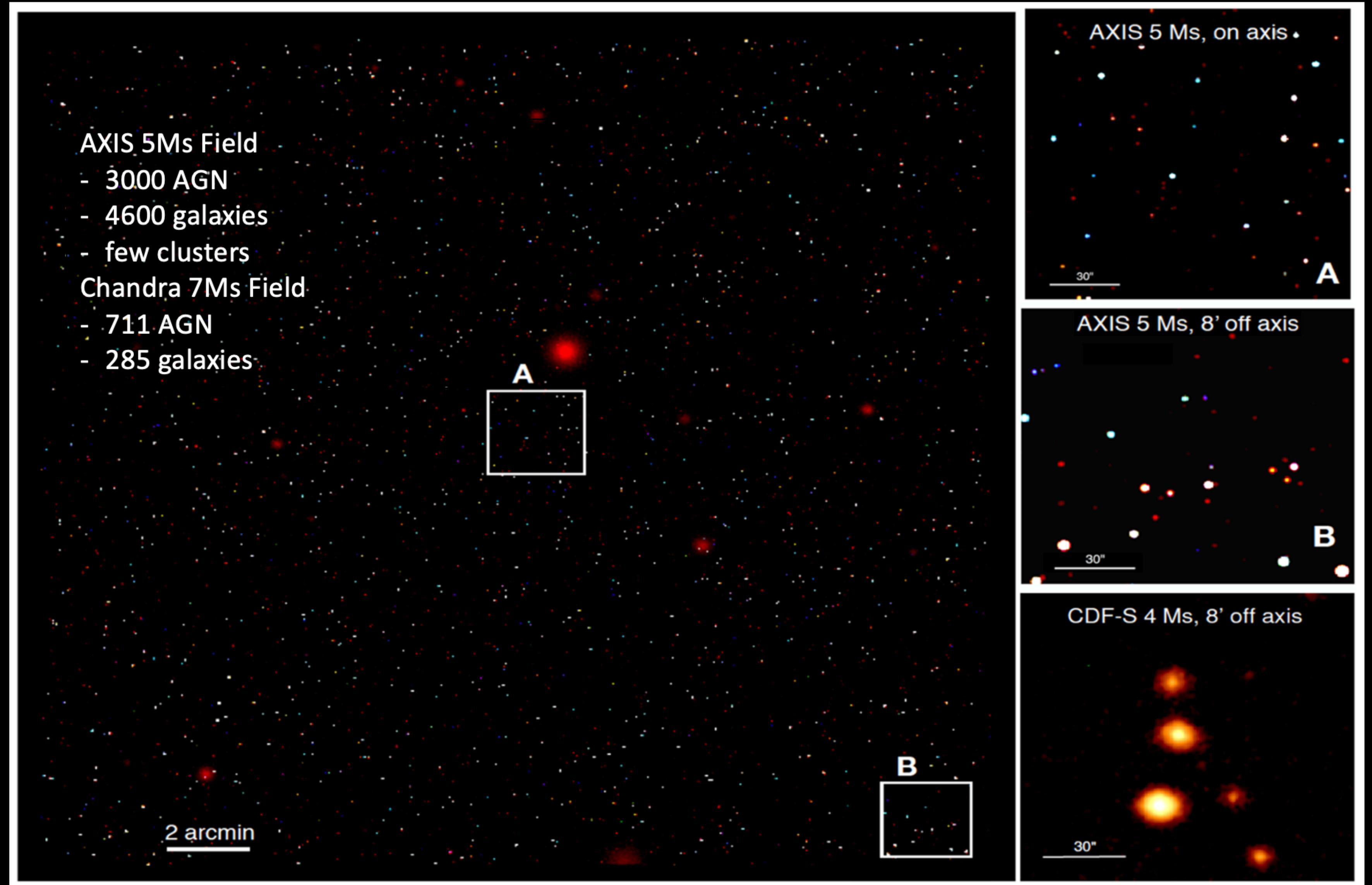
*B-Q1: “What are the **mass and spin distributions** of neutron stars and stellar mass black holes?”*

Direct Measurements



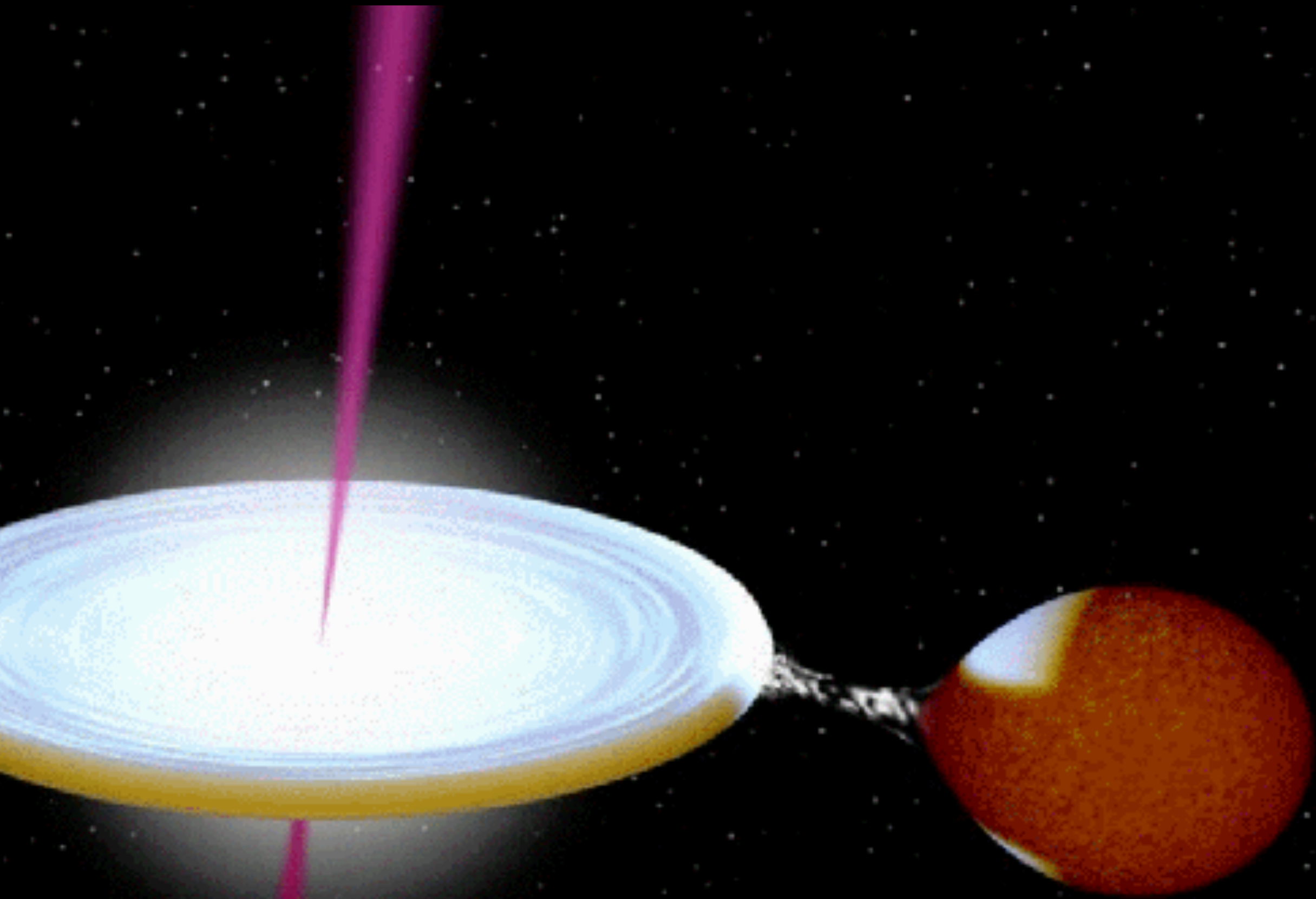
PI: Chris Reynolds, UMD
DPI: Erin Kara, MIT

axis.astro.umd.edu

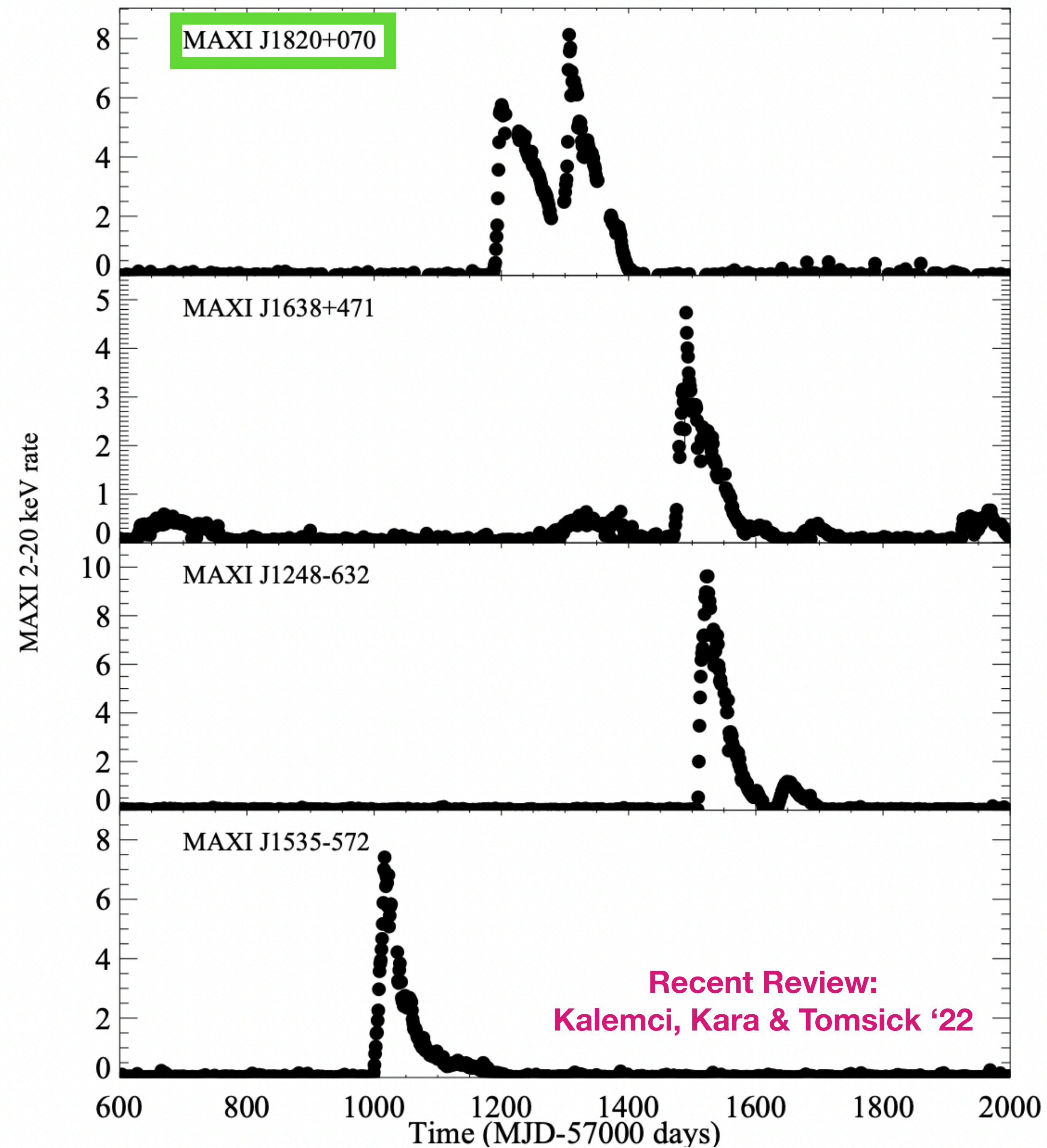


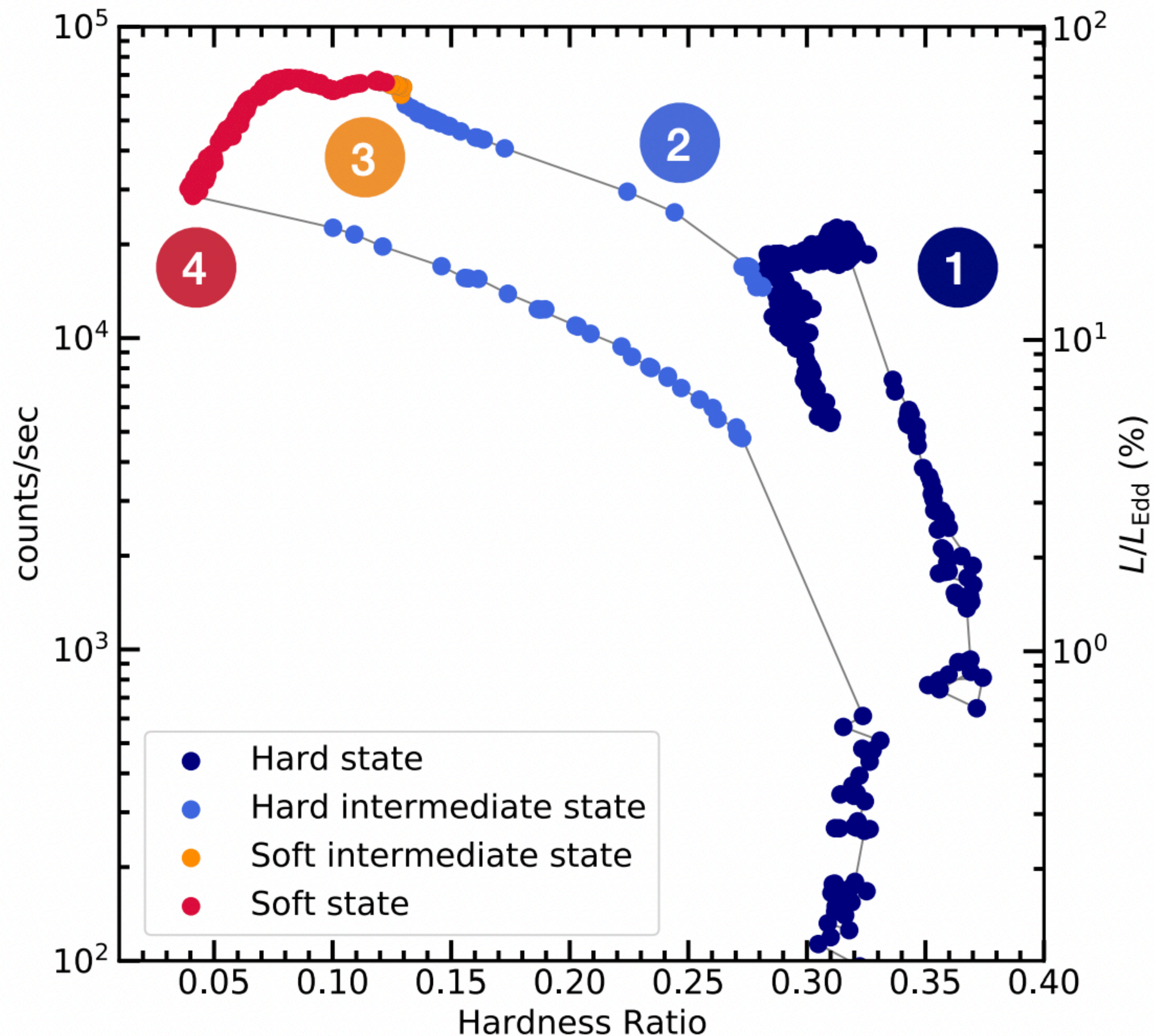
Simulation from Edmund Hodges-Kluck

Black hole transients



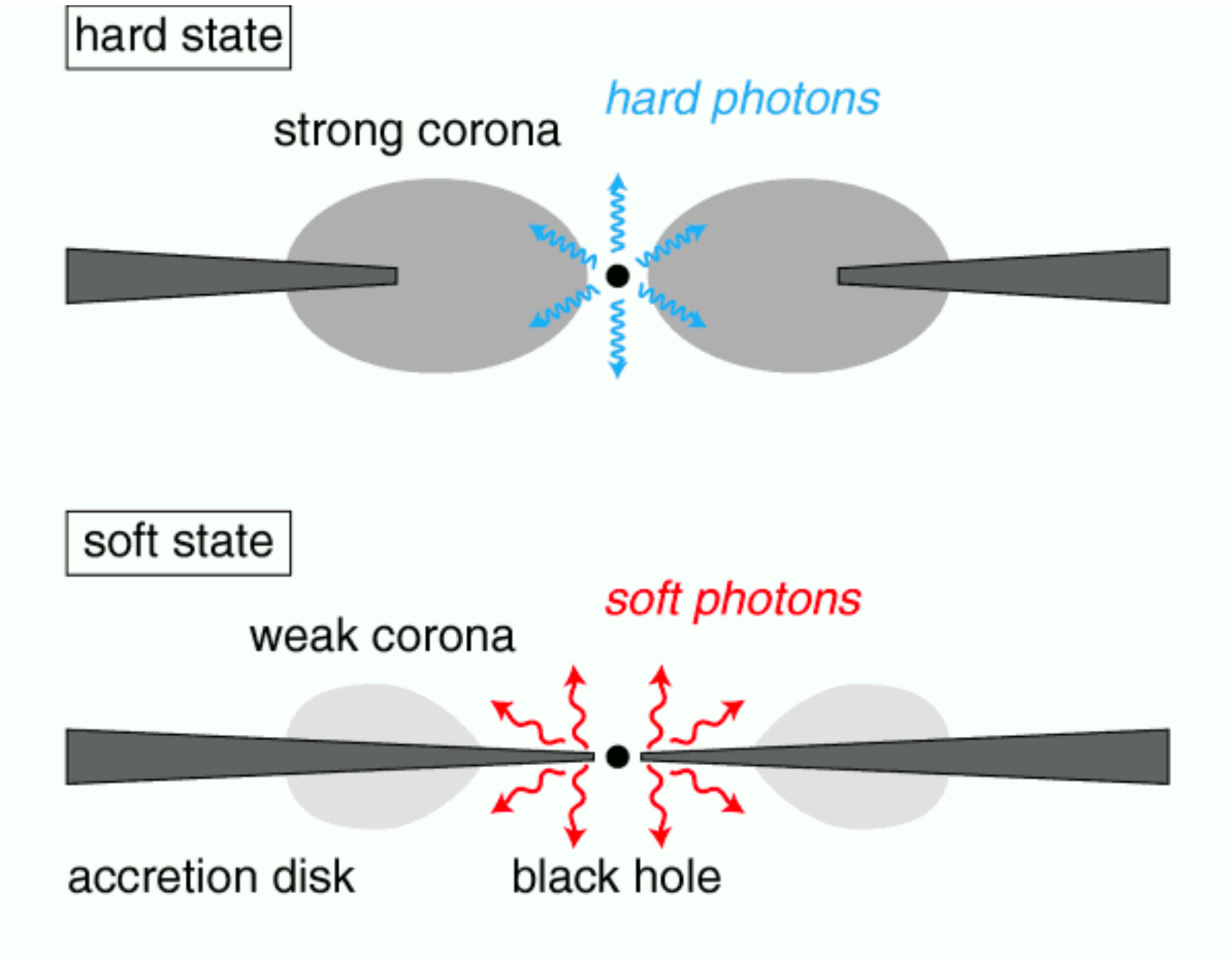
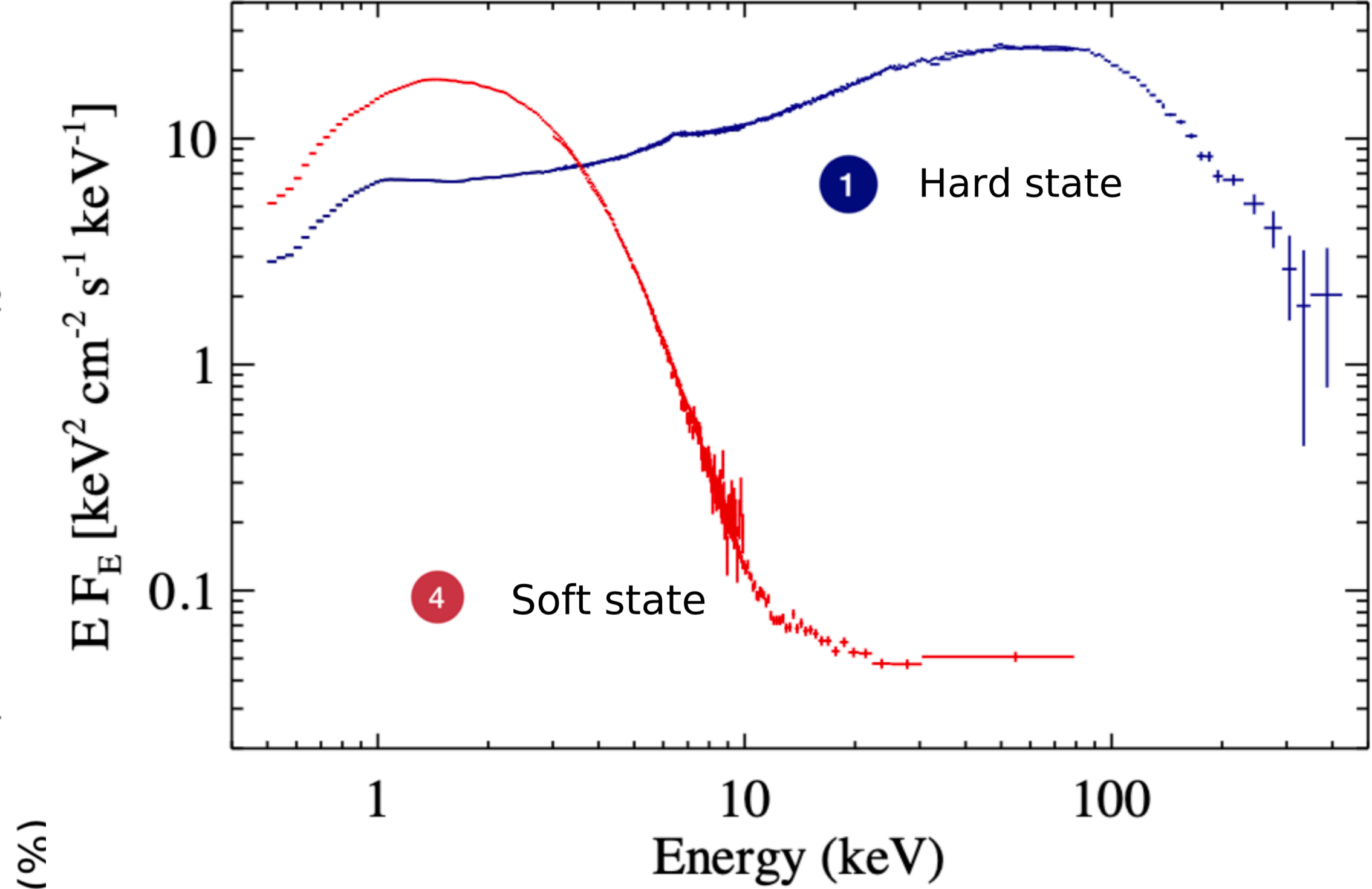
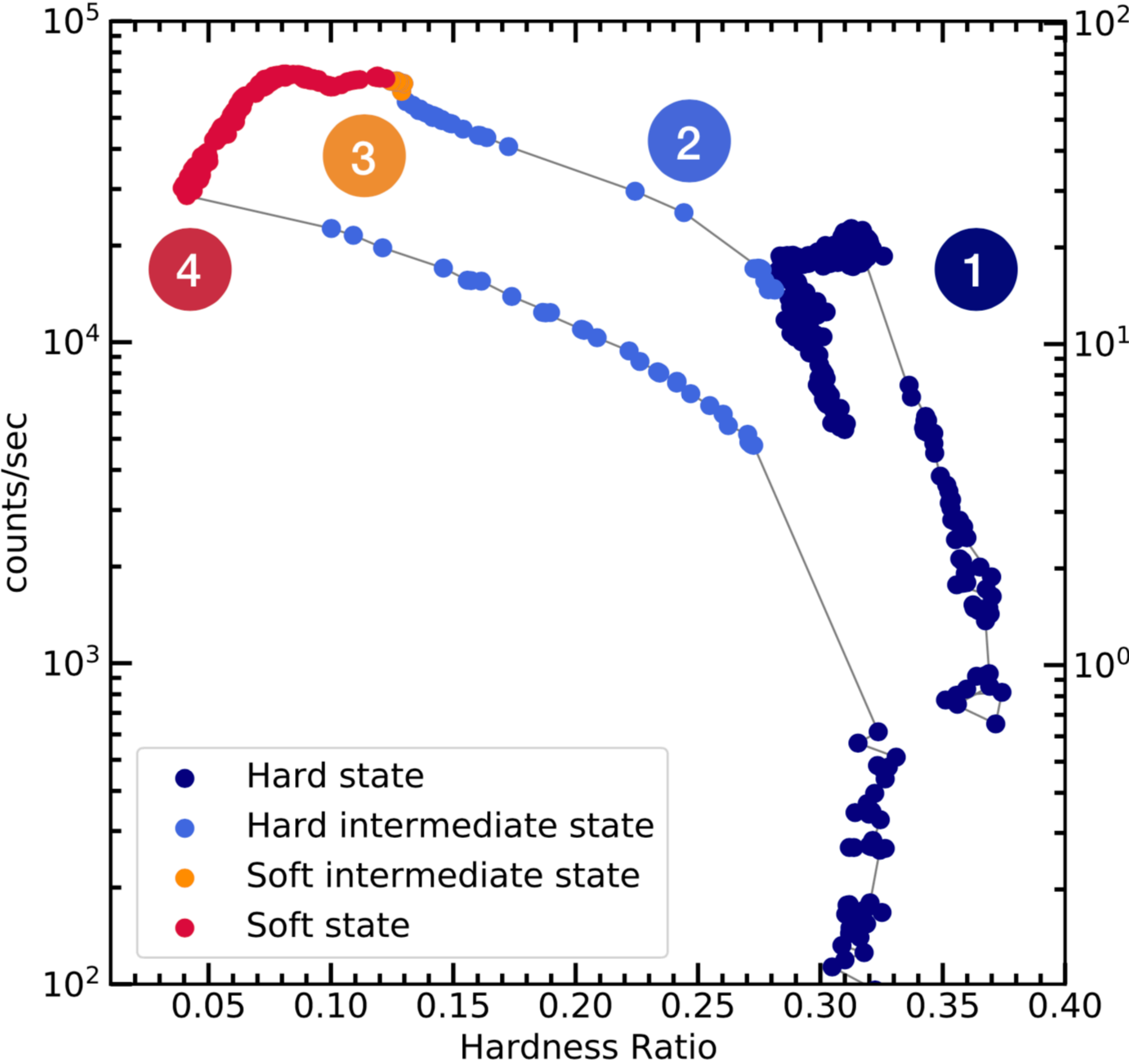
**Causal connection
between accretion & ejection**



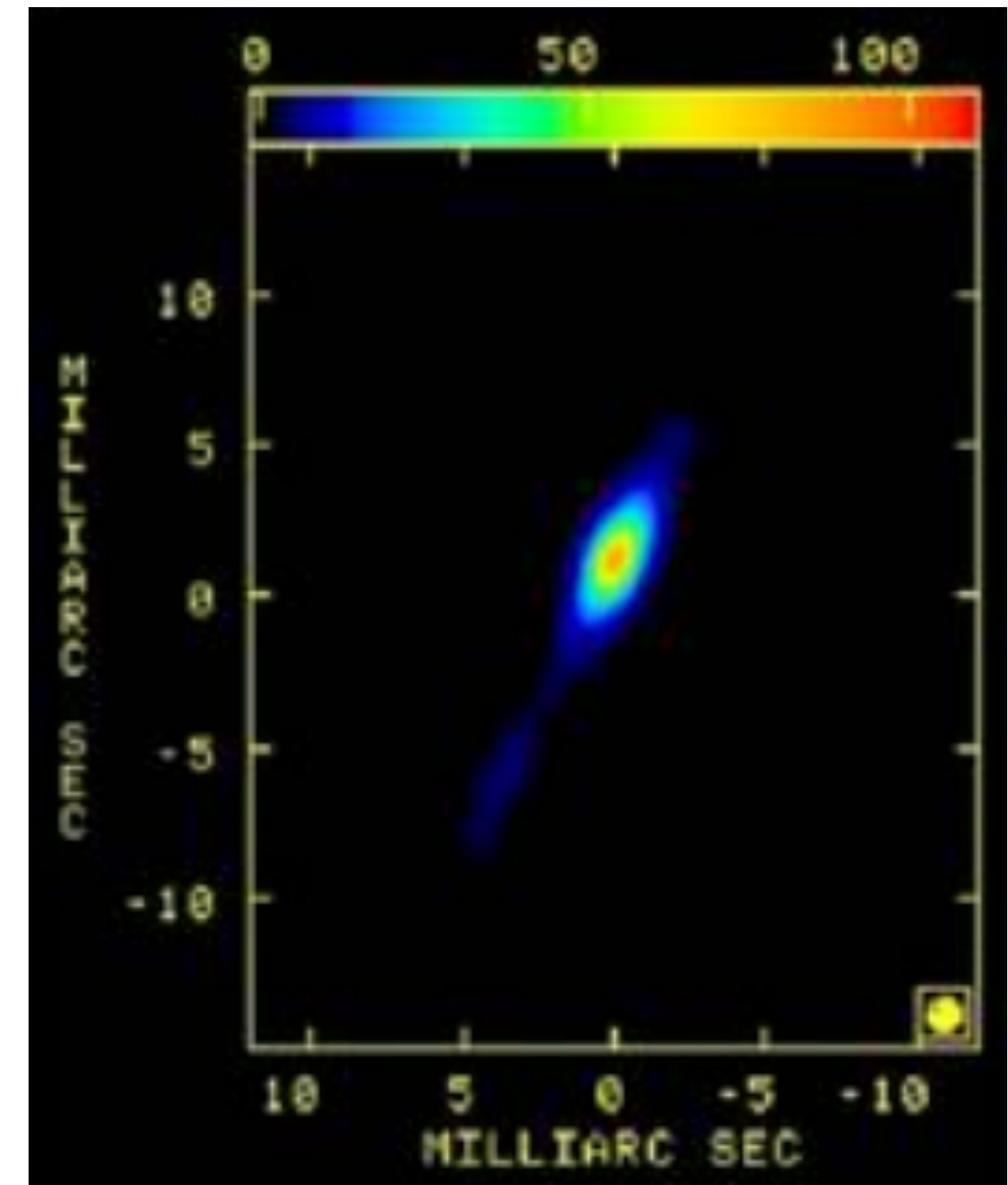
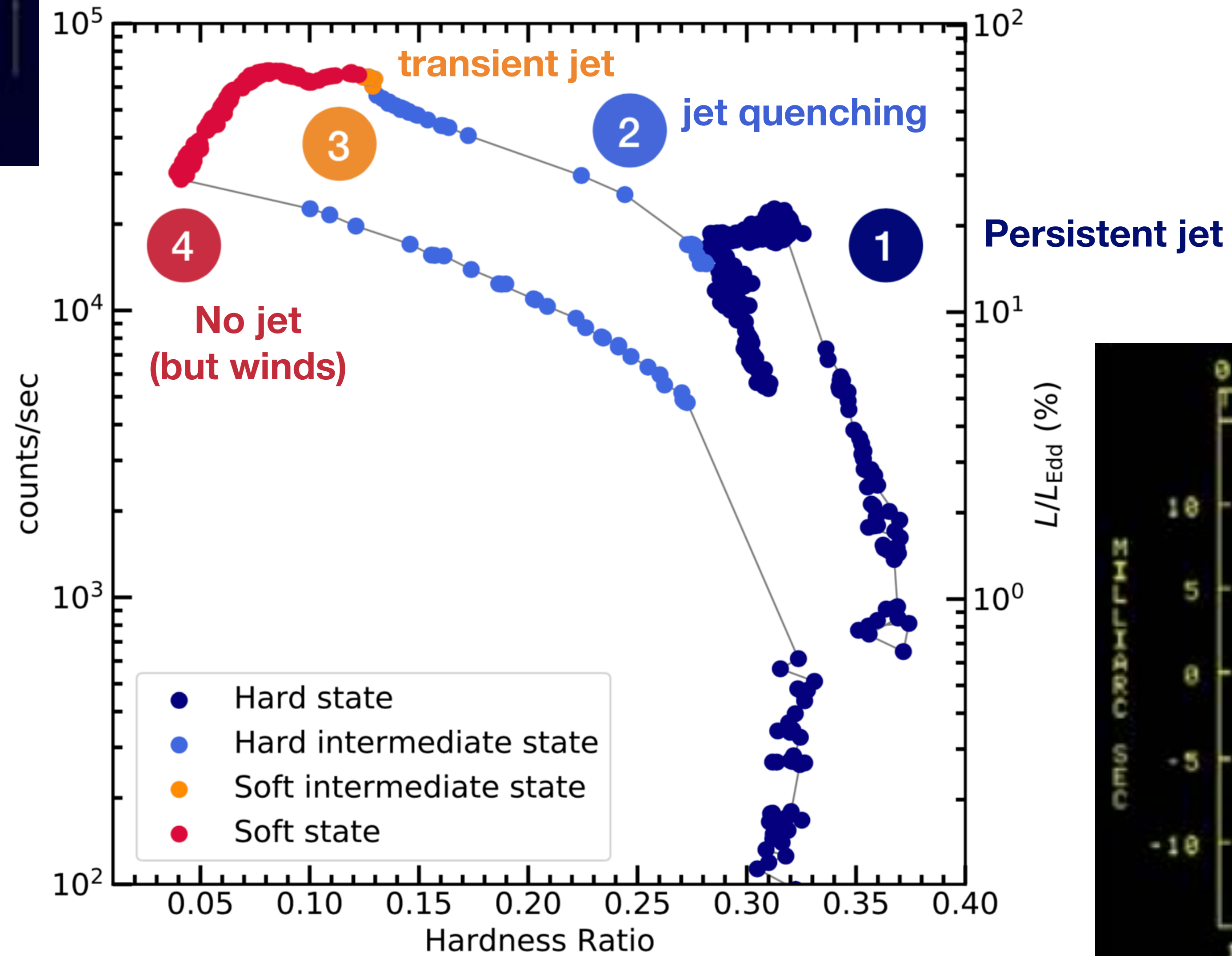
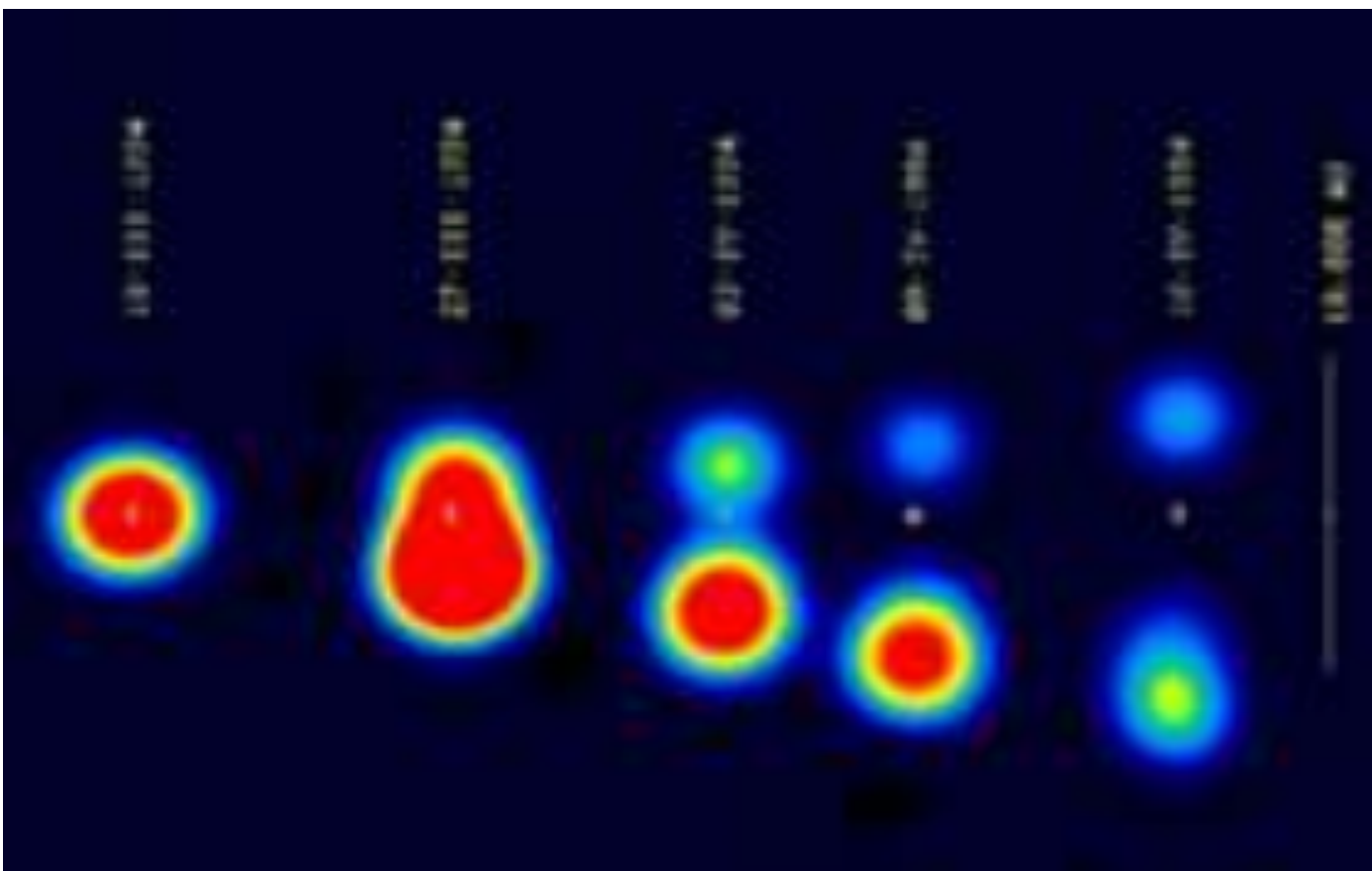


- 1 Hard State**
 - Hardest corona, weak disk
 - Compact radio jet
 - Iron line and Compton hump
 - Highest RMS: Type C QPOs, Reverberation lags
- 2 Hard Intermediate State (HIMS)**
 - Softening corona, stronger disk
 - Compact radio jet shuts down
 - Iron line and Compton hump
 - High RMS: Type C QPOs, Reverberation lags
- 3 Soft Intermediate State (SIMS)**
 - Still softer corona, stronger disk
 - Ballistic radio jet
 - Iron line and Compton hump
 - Low RMS: Transition from Type C to B QPOs
- 4 Soft State**
 - Weak corona, strong disk
 - No radio jet, equatorial winds
 - Less prominent iron line and Compton hump
 - Low RMS: Rarely Type A QPOs, no lags

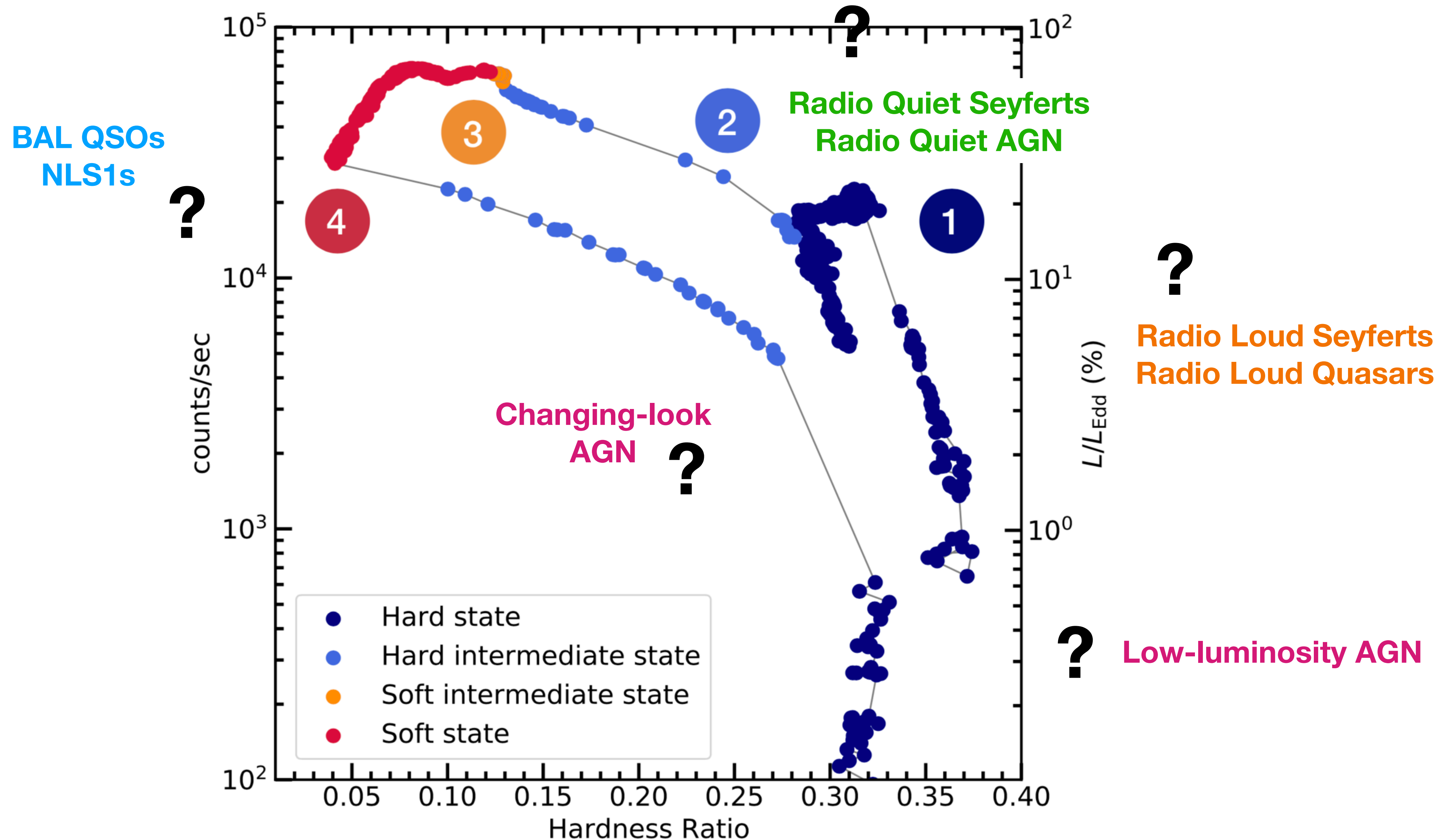
Black hole transients and accretion evolution



Universal Disc-Jet Coupling in black holes

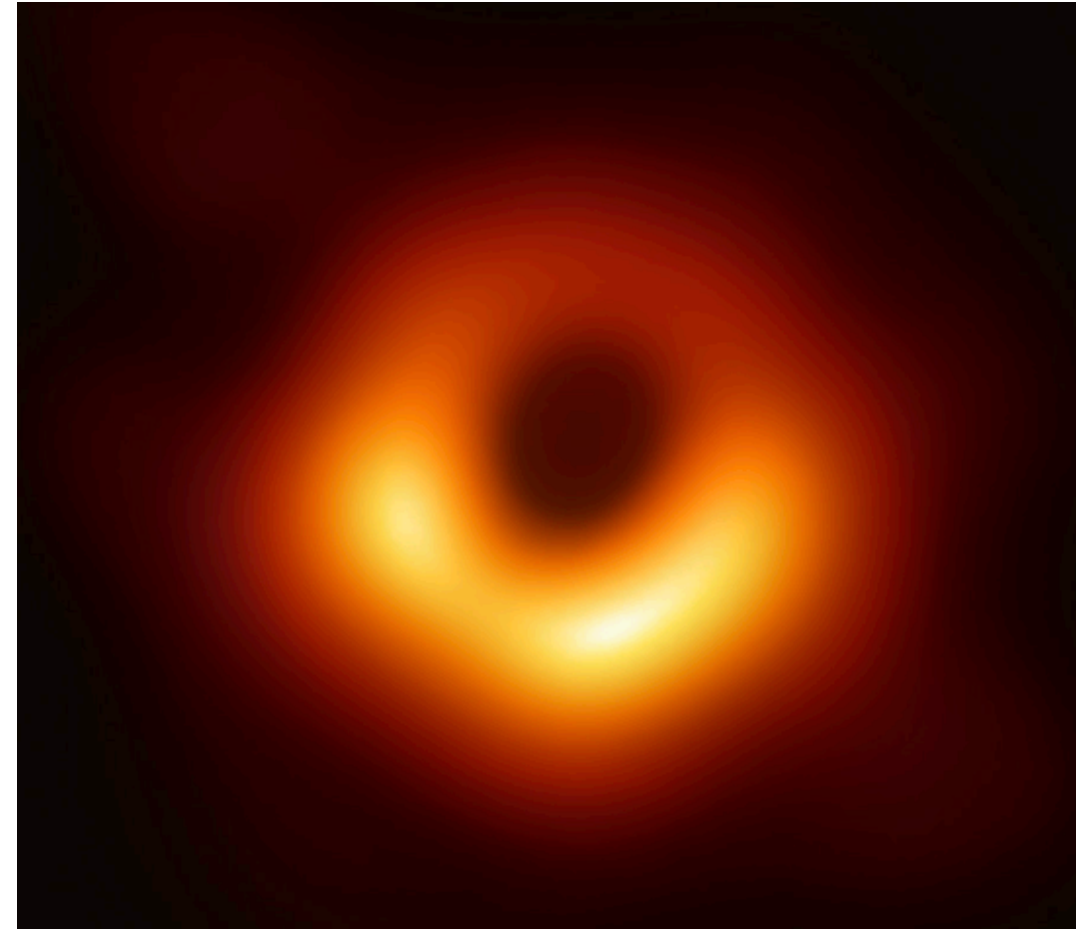


Black hole transients: analogous to AGN?

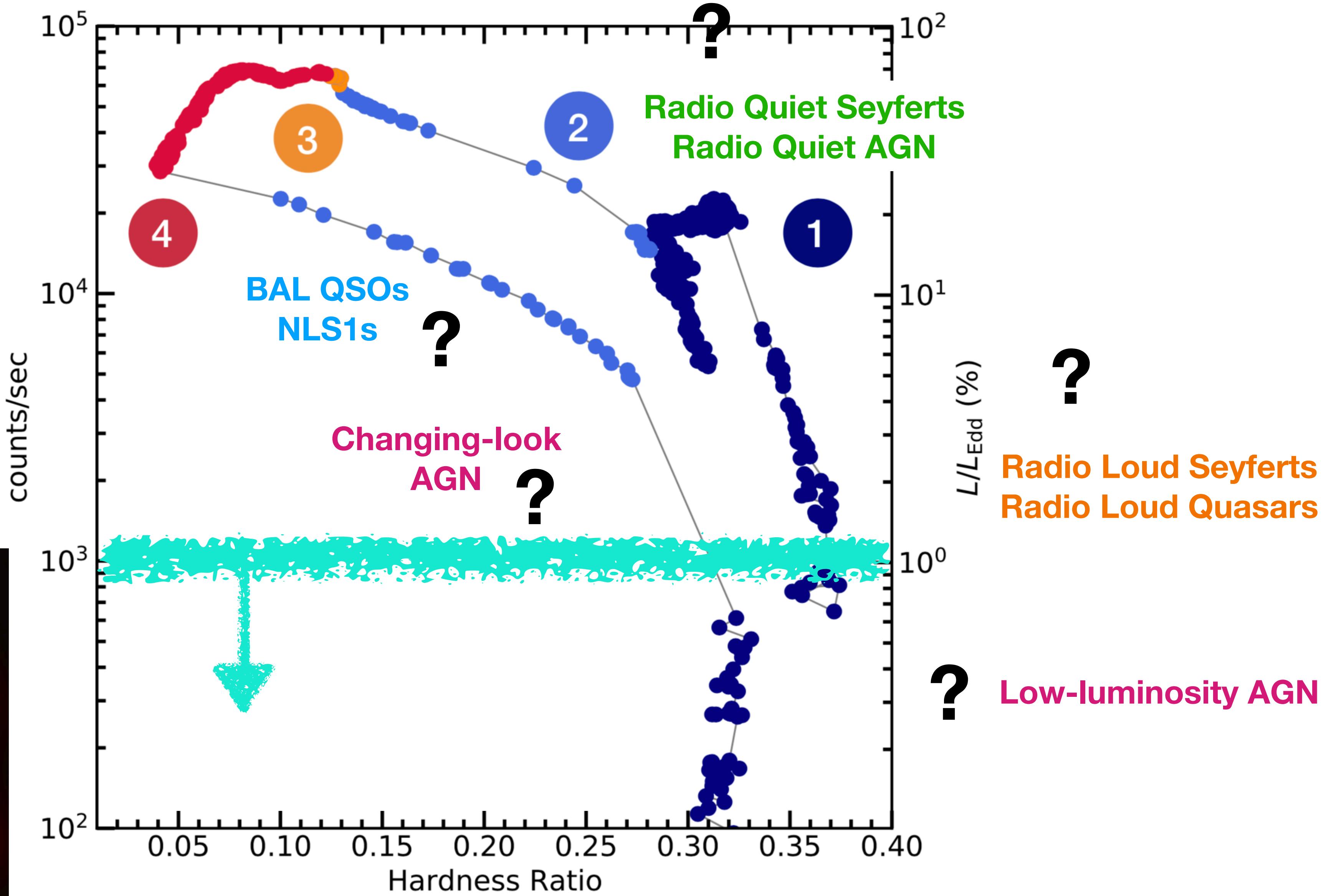


Equivalent duty cycle in AGN is millions++ of years

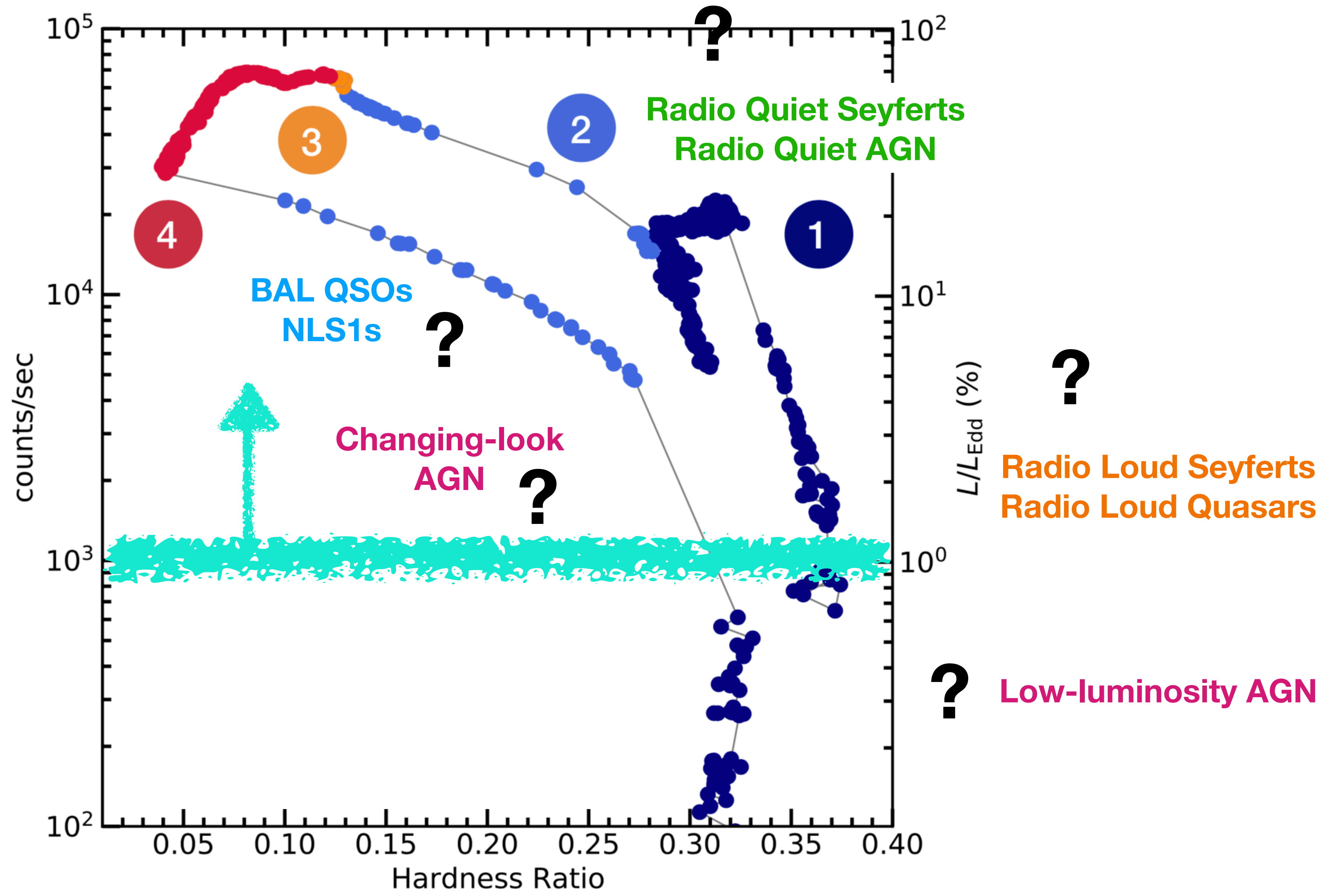
Event Horizon Scales of Accretion



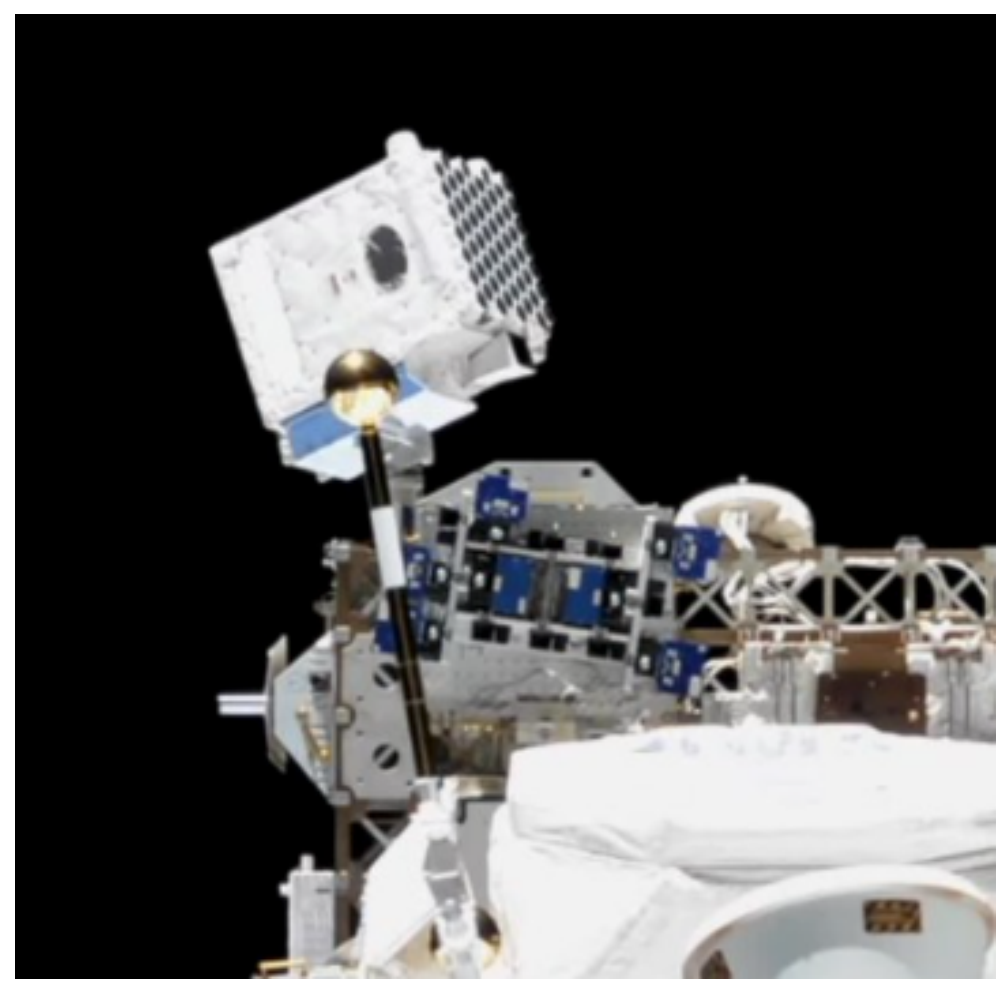
Optically-thin regime:
EHT & ngEHT !



Event Horizon Scales of Accretion

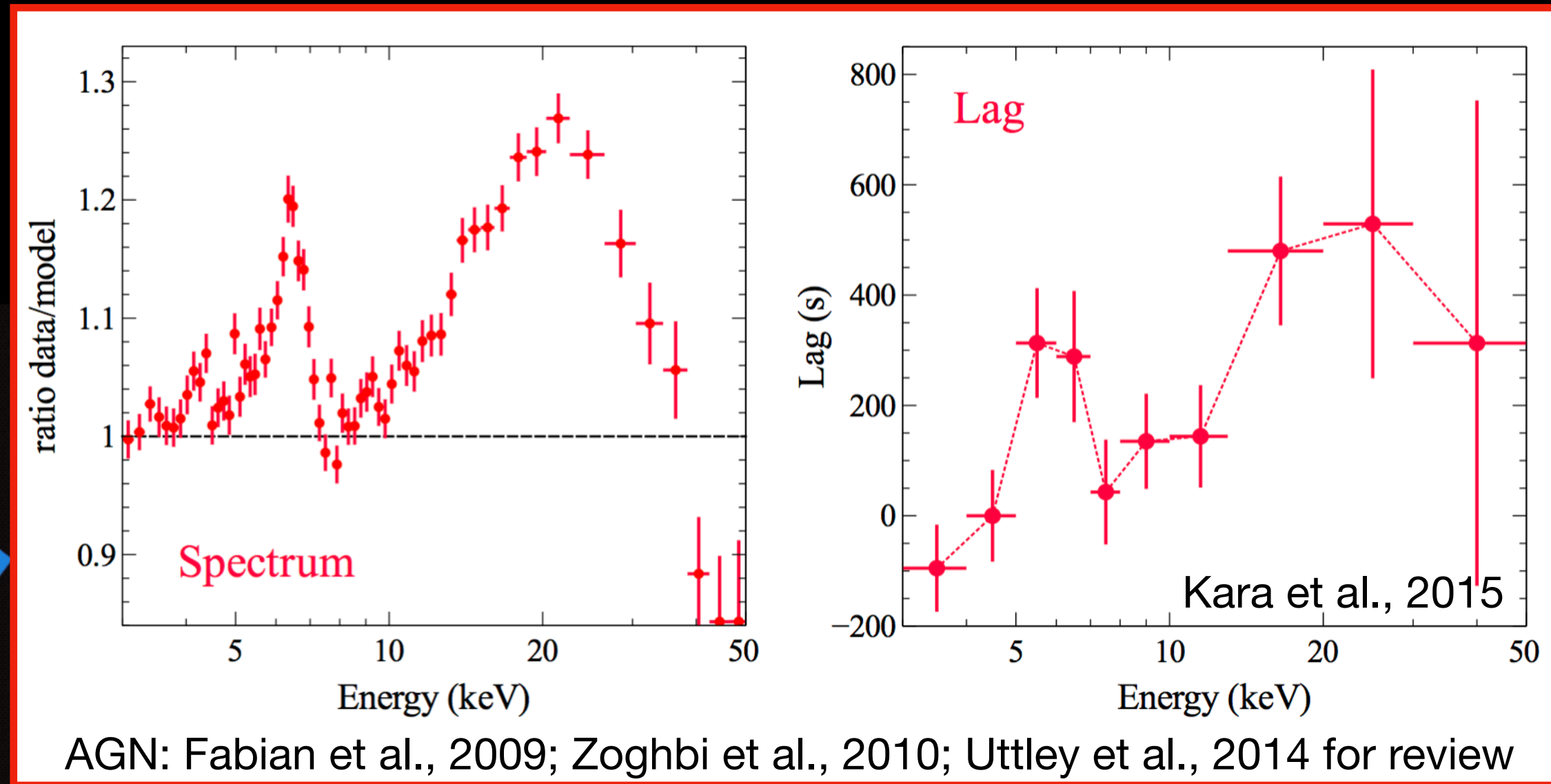


Optically-thick regime:
X-ray Reverberation
Mapping

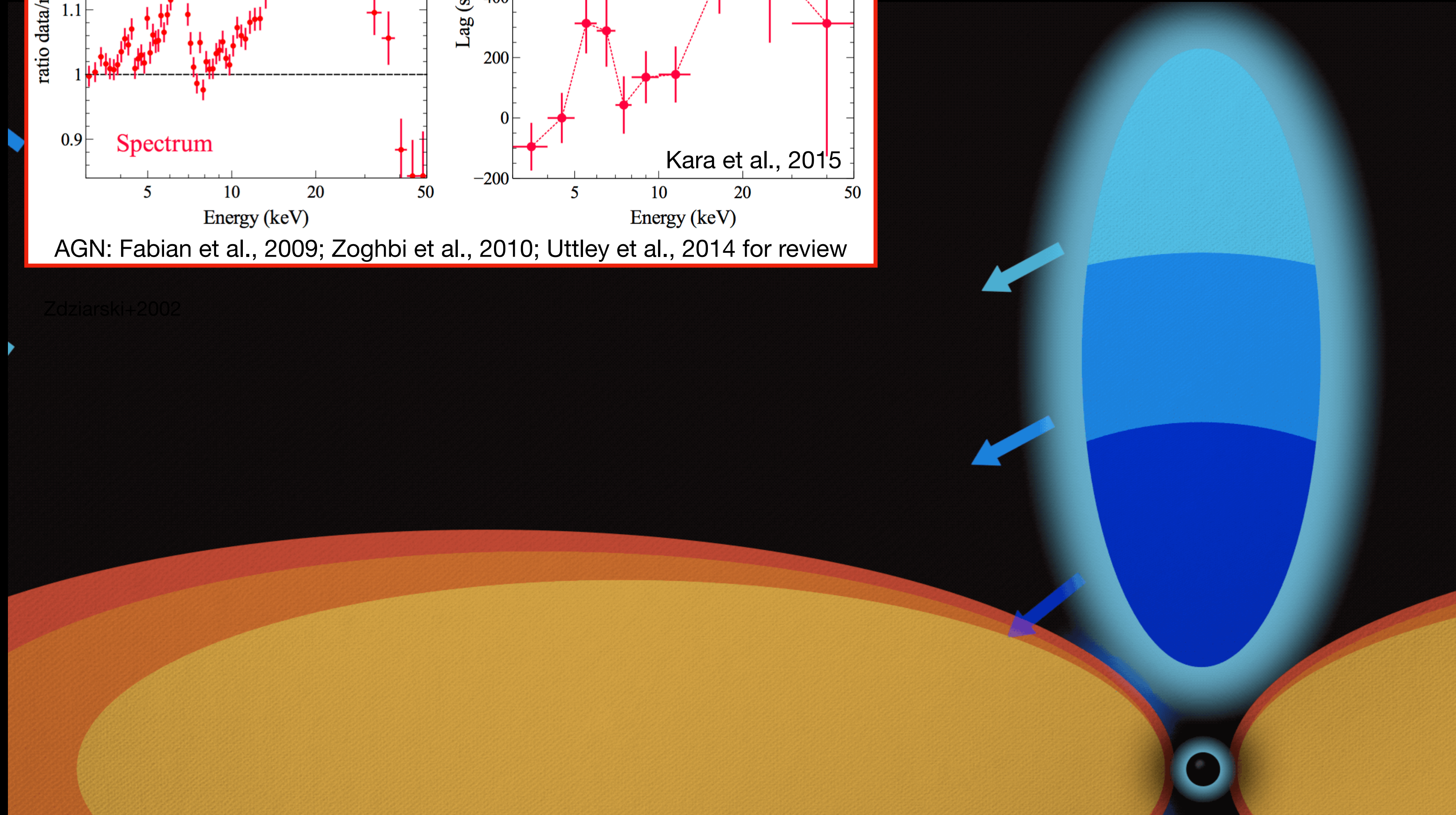


“Swap spatial resolution
for time resolution”

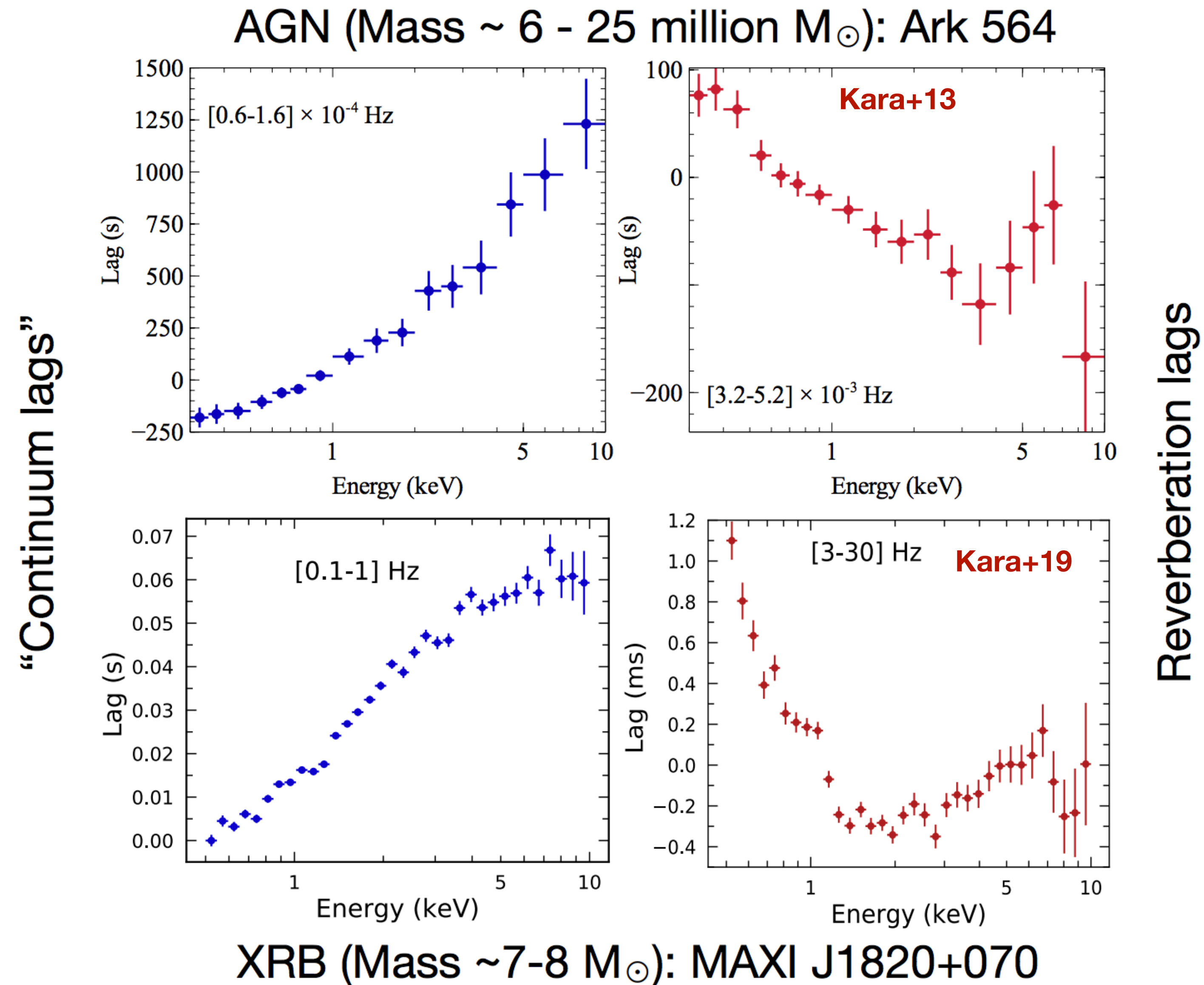
Reverberation Mapping with NICER



Zdziarski+2002



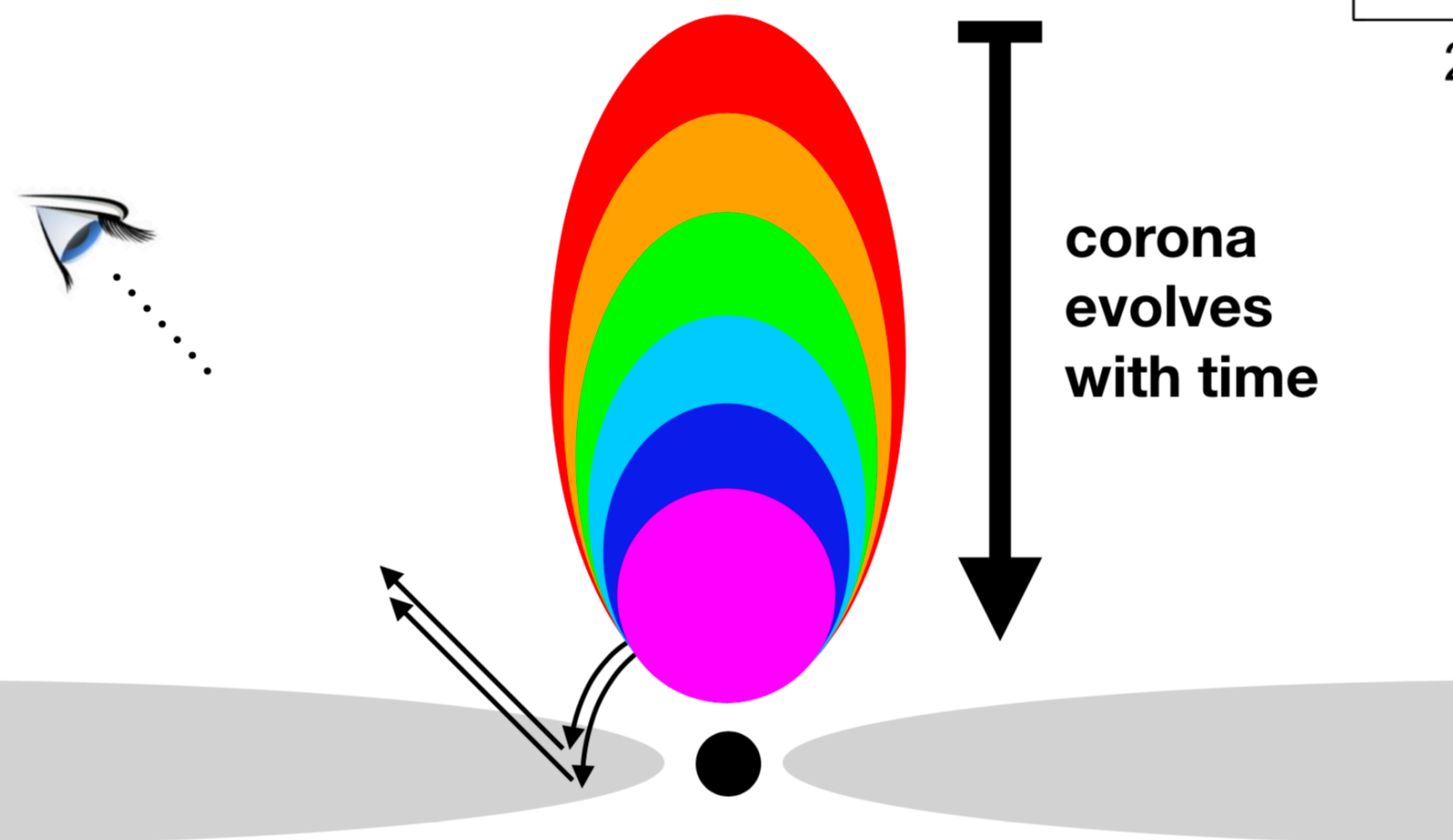
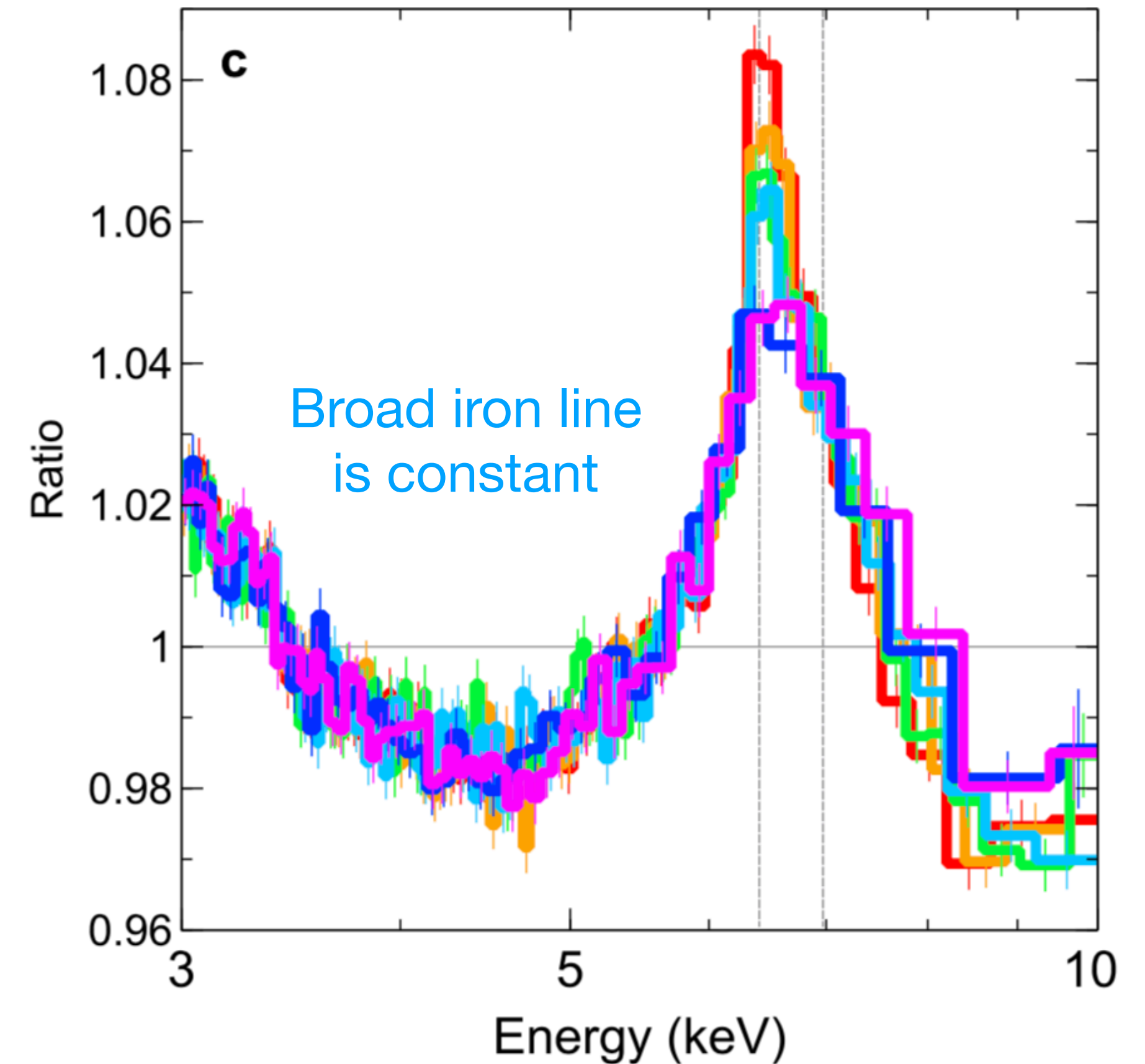
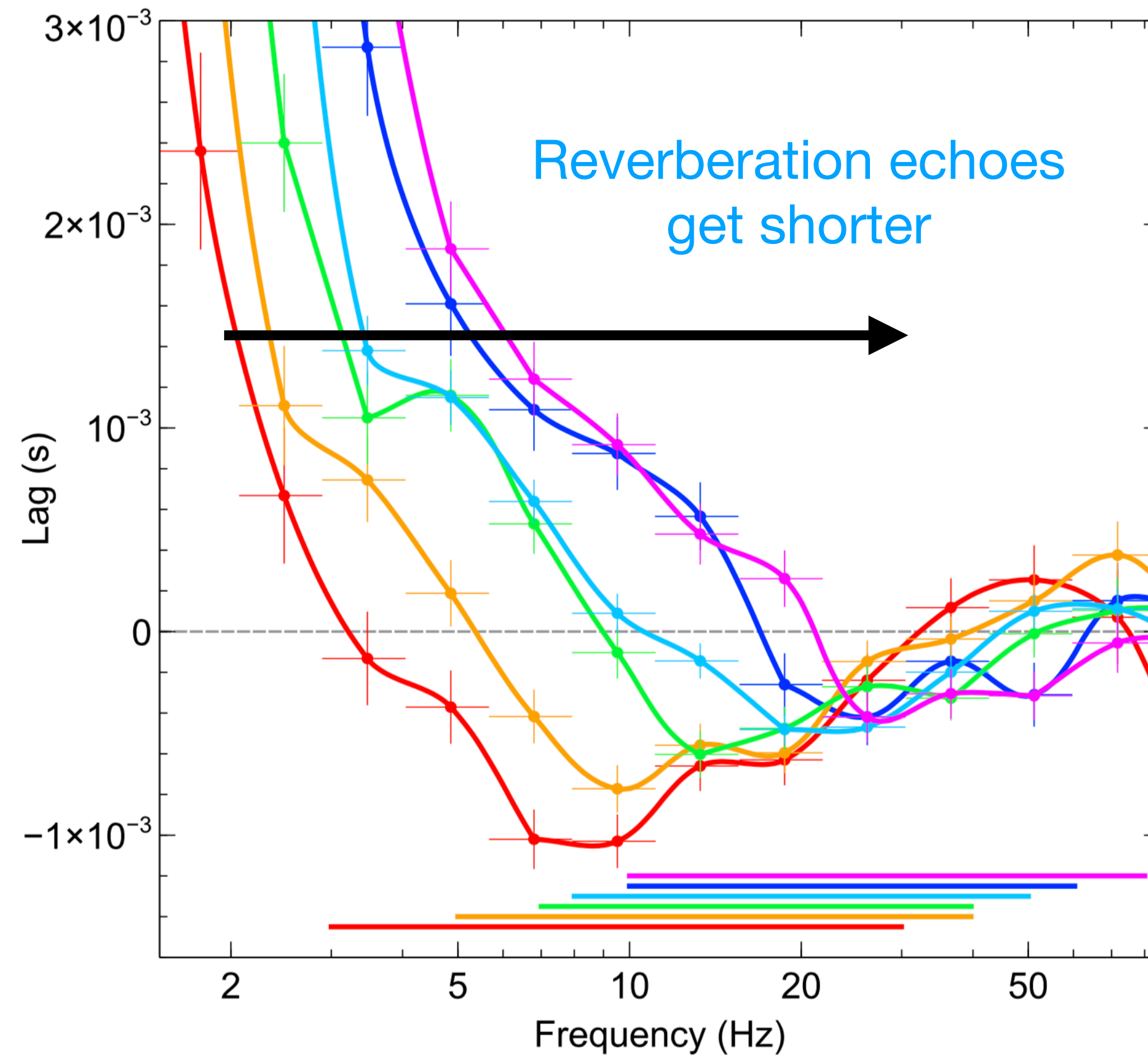
Black Hole X-ray Binaries as “Micro-Seyferts”?



Inner accretion flow geometry from reverb mapping



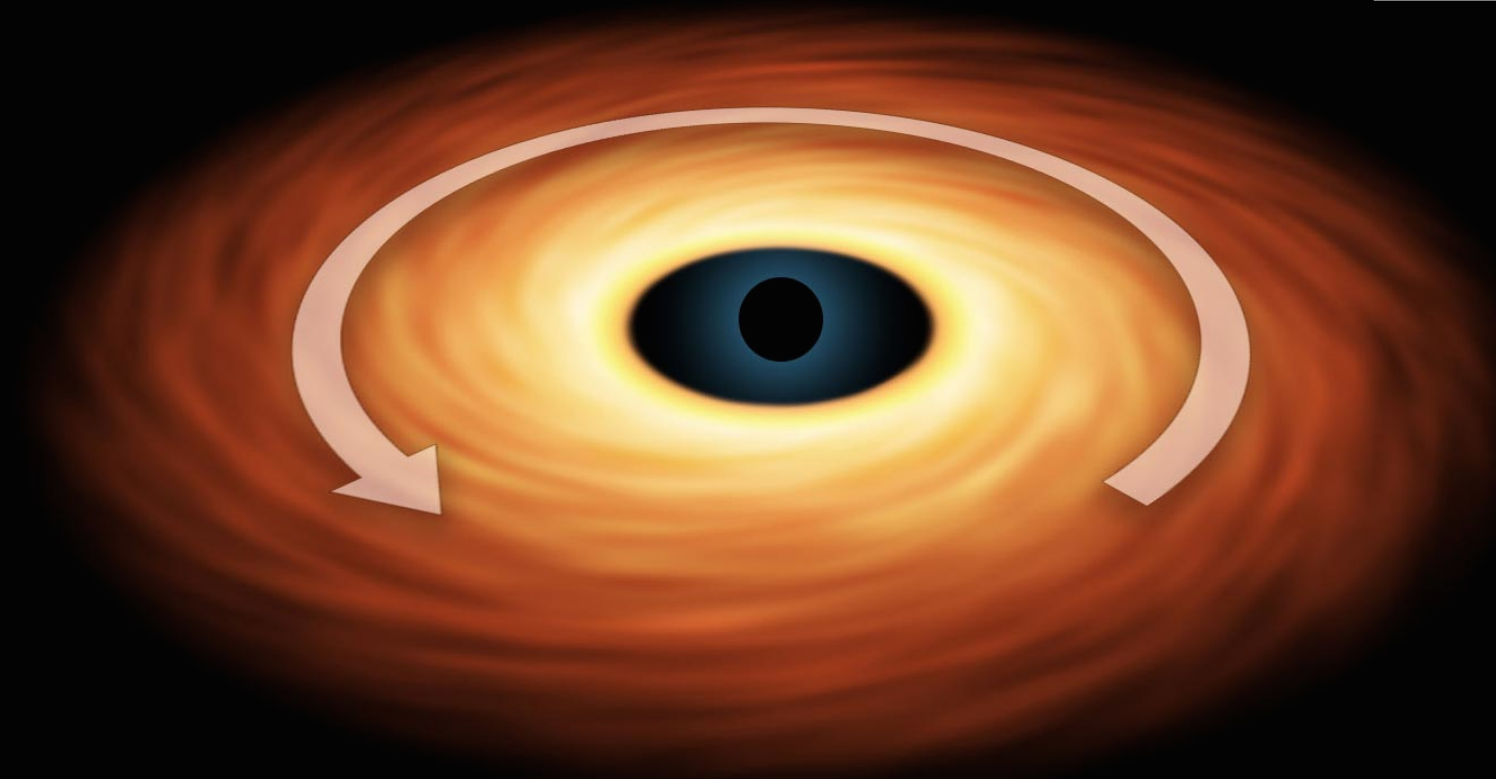
Kara et al., 2019



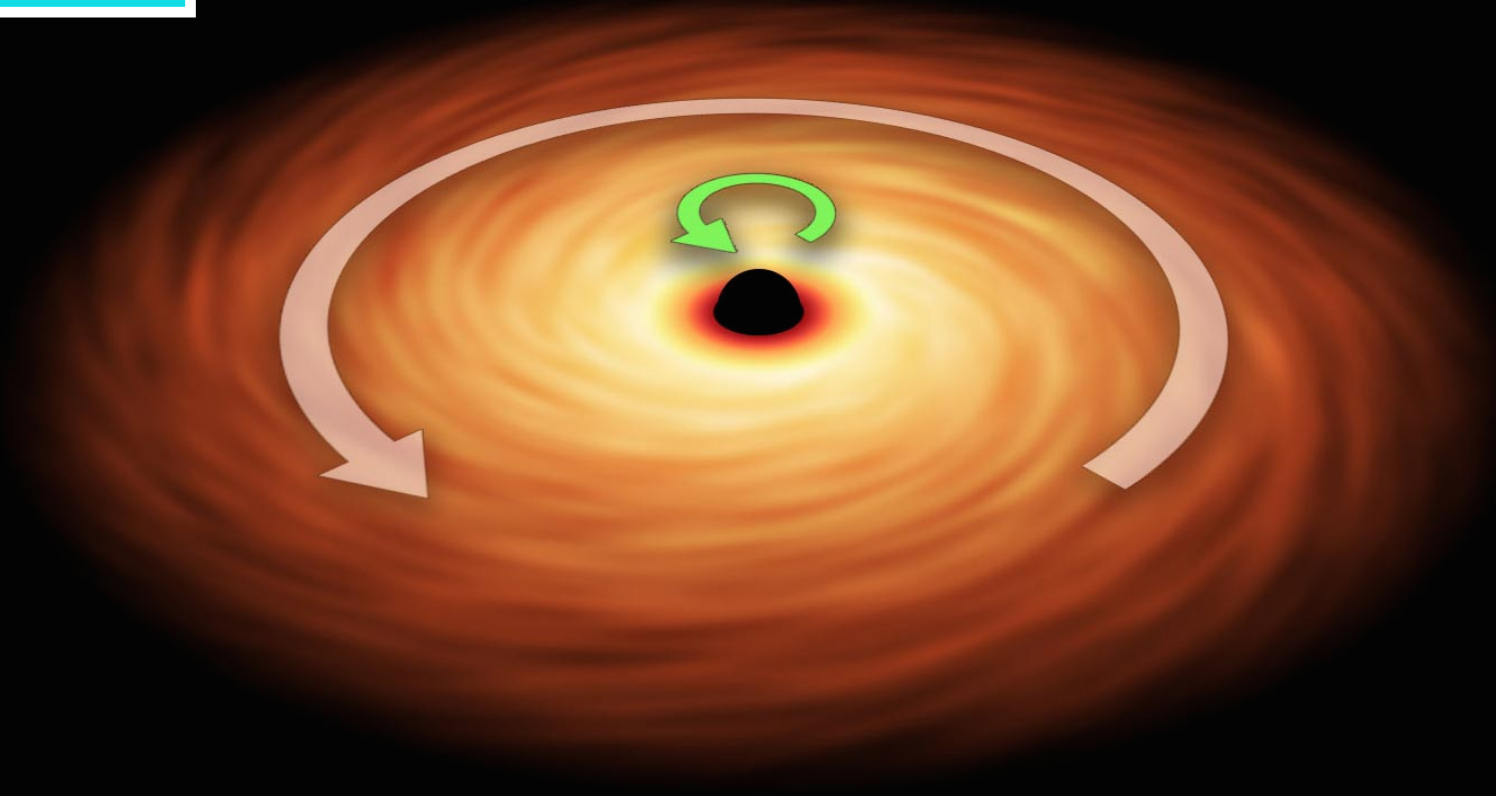
We understand the disk geometry well enough to measure **black hole spin**

The importance of black hole spin

$$L = \epsilon \dot{M} c^2$$



Non-spinning black hole
 $r_{\text{isco}} = 6 r_g$

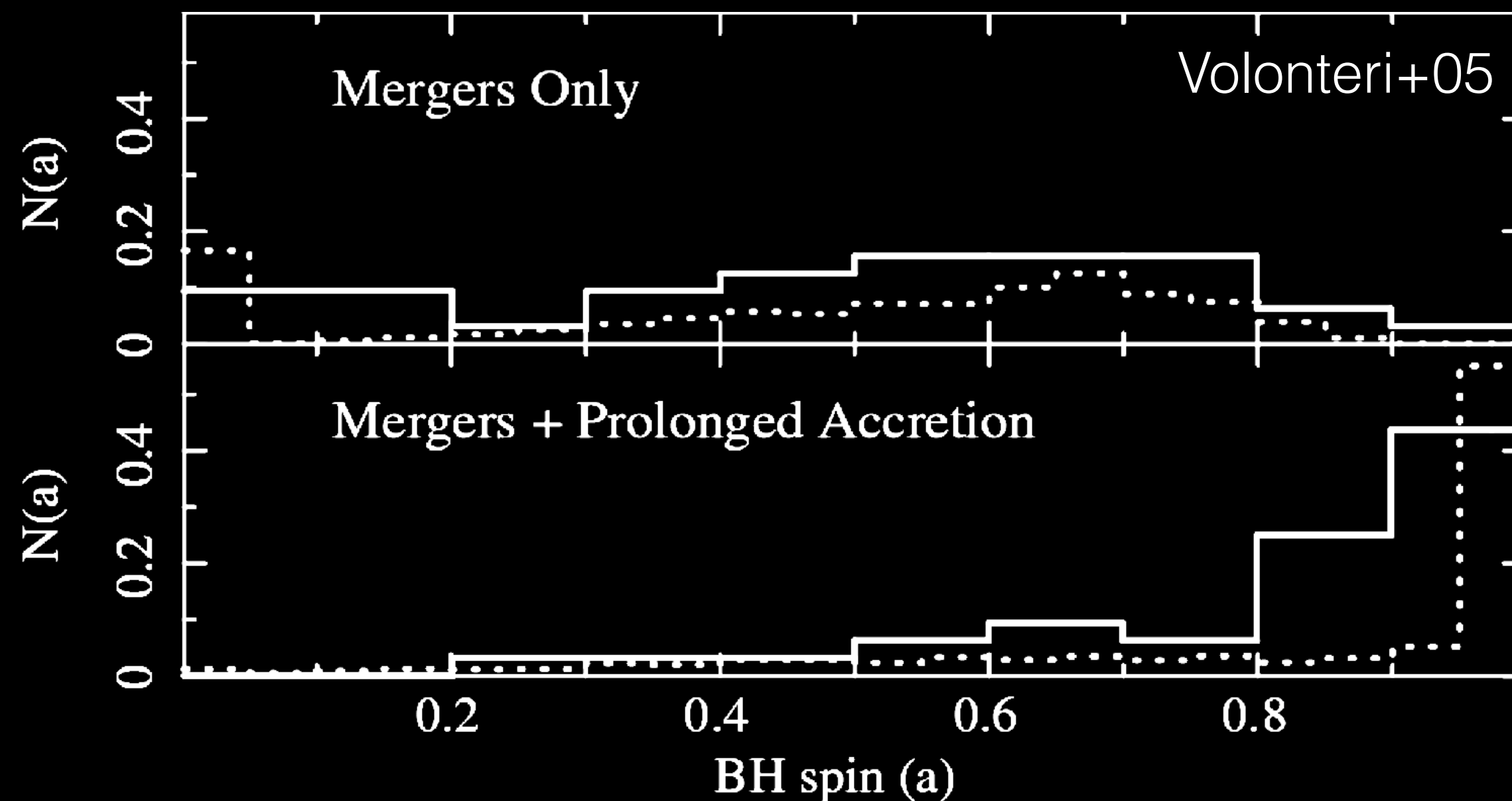


Prograde rotation
 $r_{\text{isco}} = 1 r_g$

B-Q2: “Why do some compact objects eject material in nearly light-speed **jets**, and what is that material made of?”

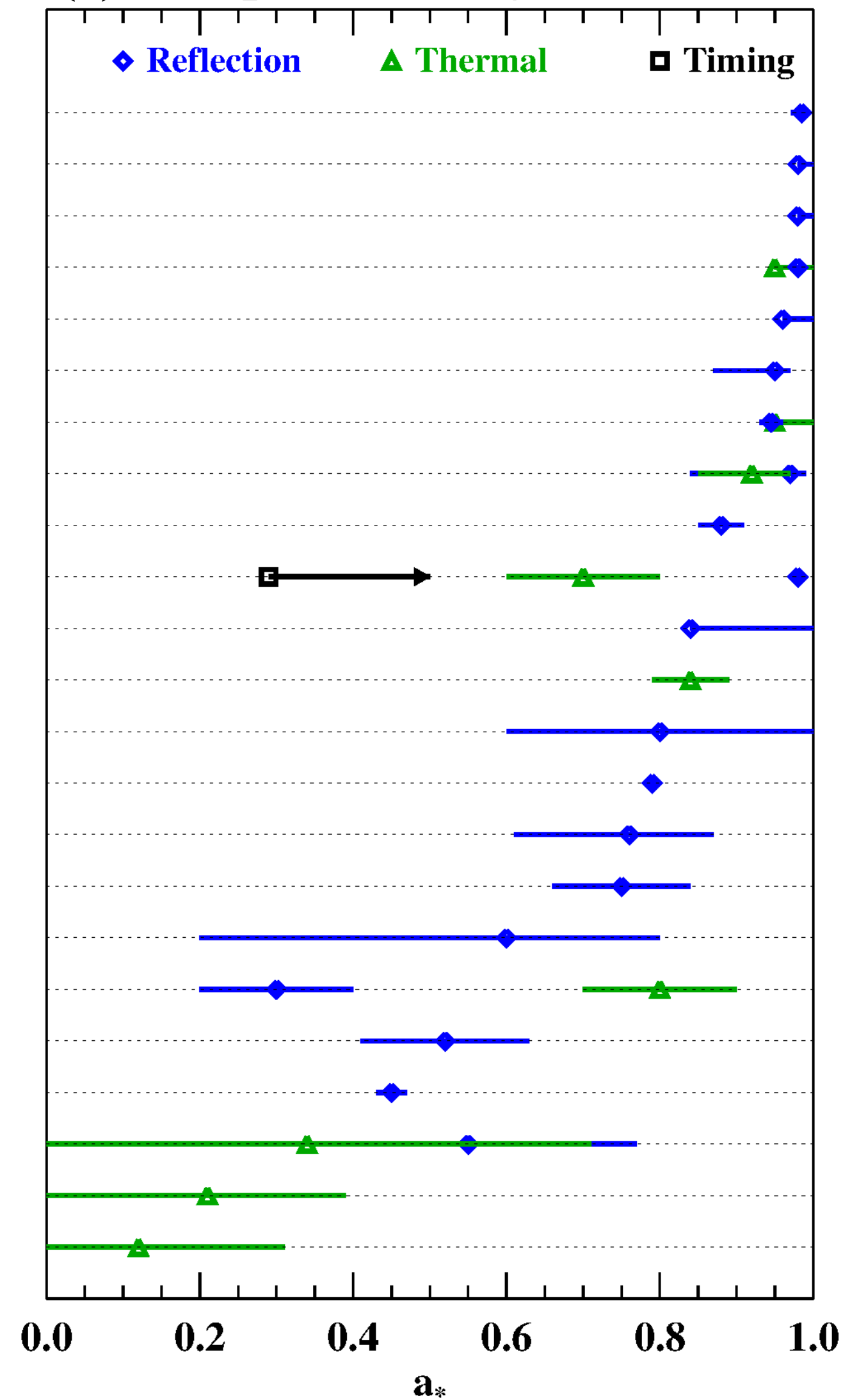
B-Q3**: “What seeds supermassive black holes, and **how do they grow**?”

B-Q1: “What are the mass and **spin distributions** of neutron stars and stellar mass black holes?”



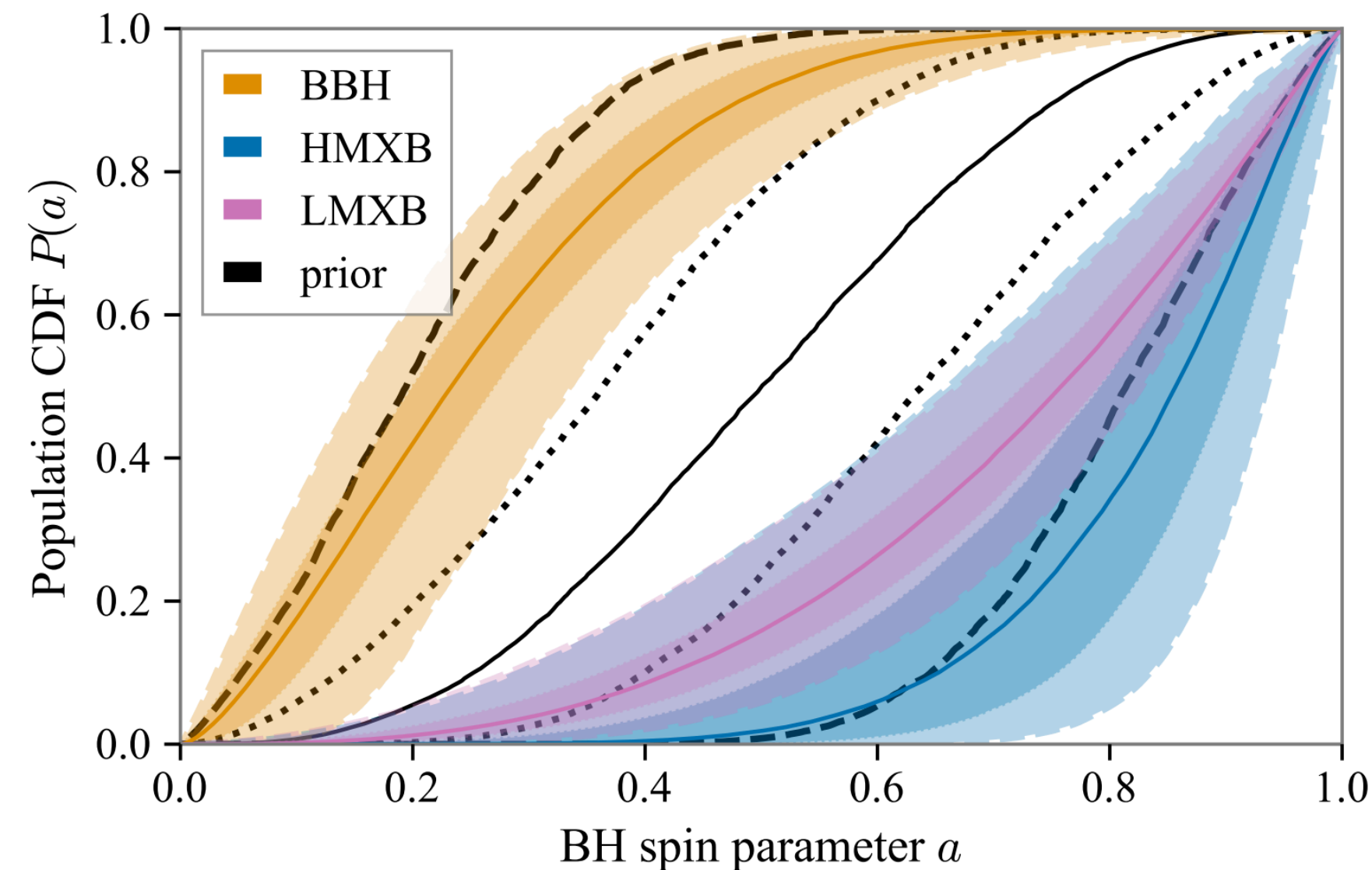
A Multi-Messenger Perspective on Black Hole Spin

(a) BH spin for X-ray binaries

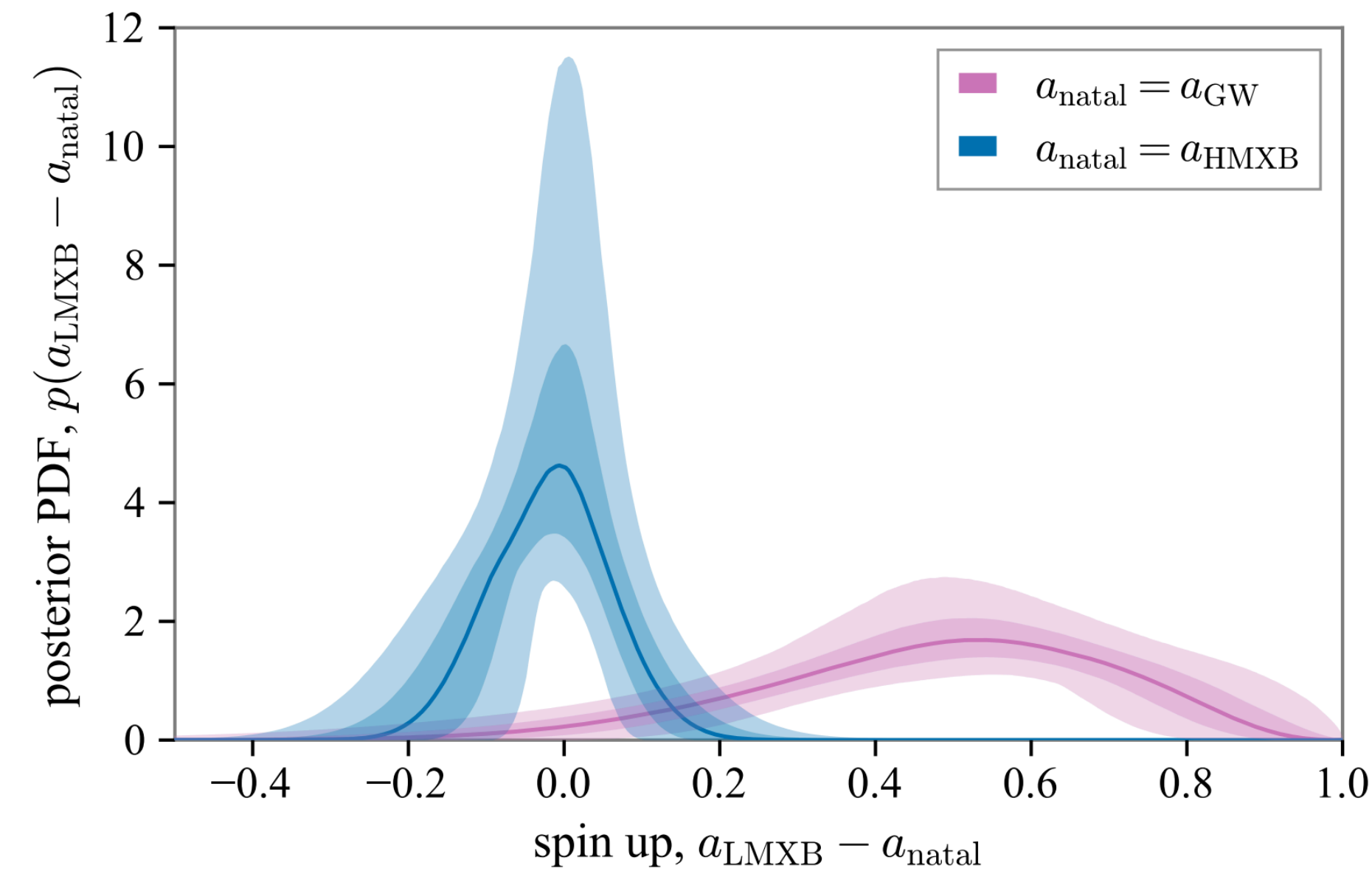


Ray+19

Fishbach & Kalogera 2022



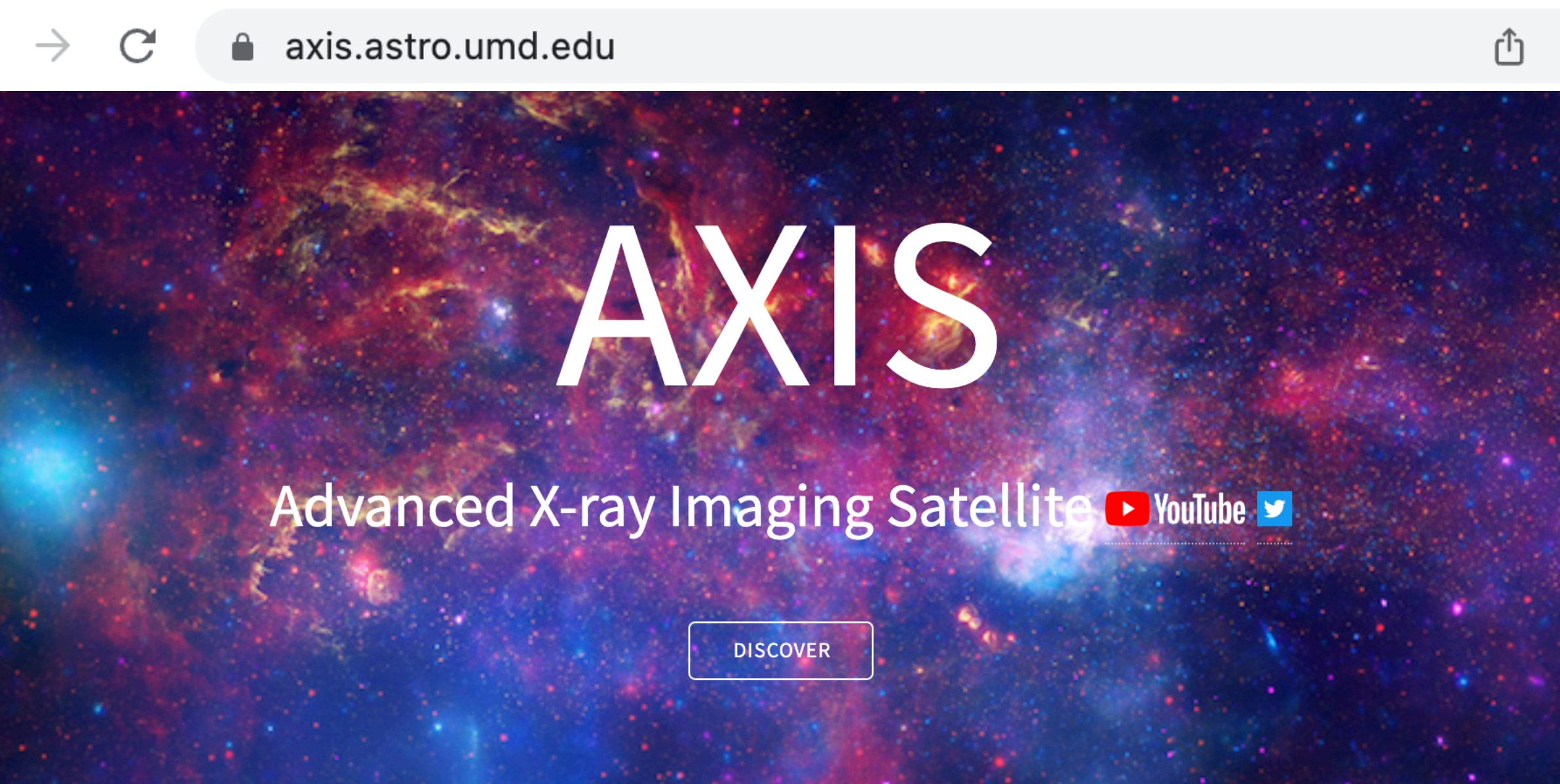
LIGO BHs are more massive and lower spin
(or at least lower X_{eff}).



Amount of spin up LMXBs must experience
if drawn from BBH population vs. HMXBs

← Mostly LMXBs where donor will never result in a BBH that LIGO would see!

Understanding X-ray Binary Populations is key to understanding LIGO BHs



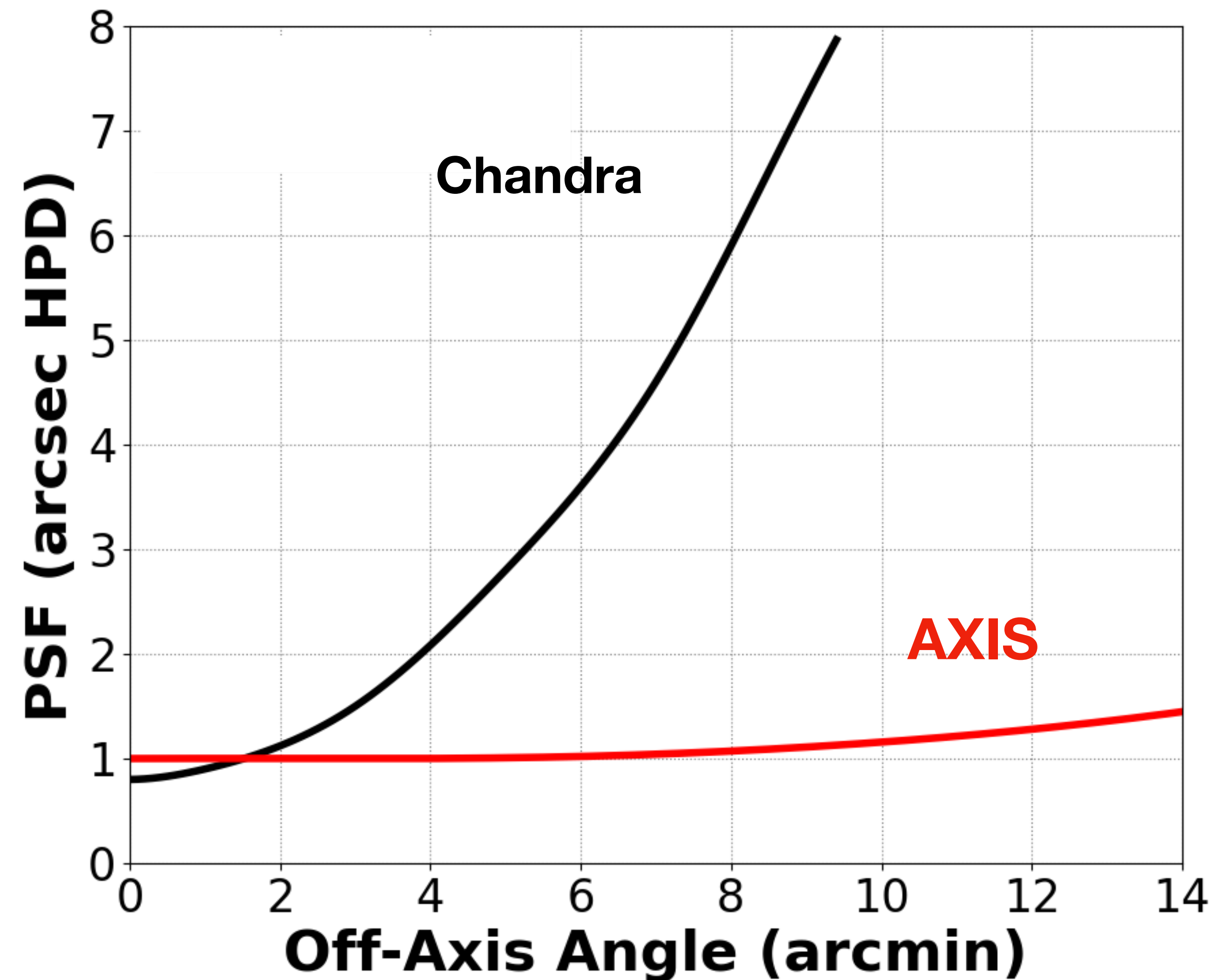
This is MMA!

1-2" PSF over
24'x24' FoV

Fast slew like Swift

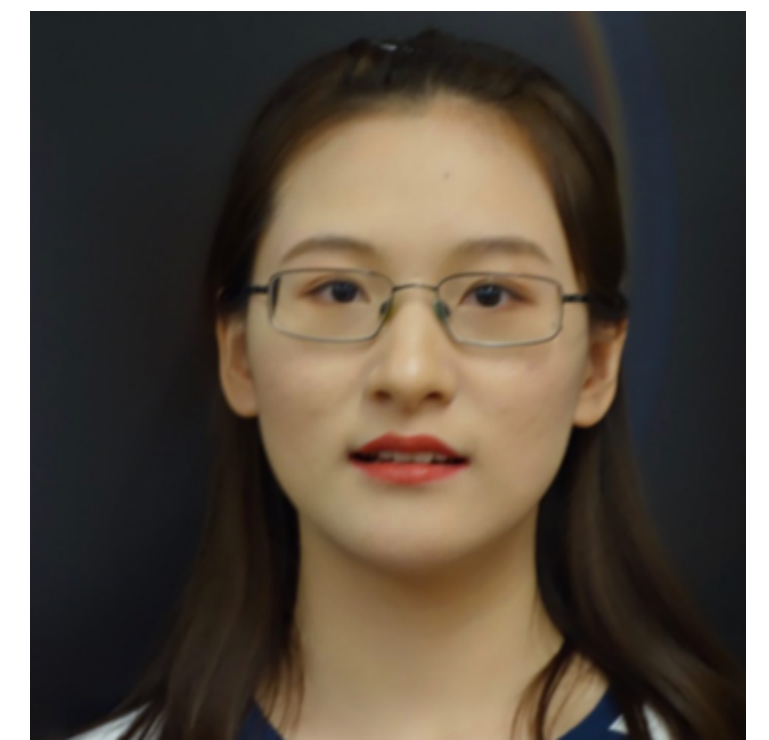
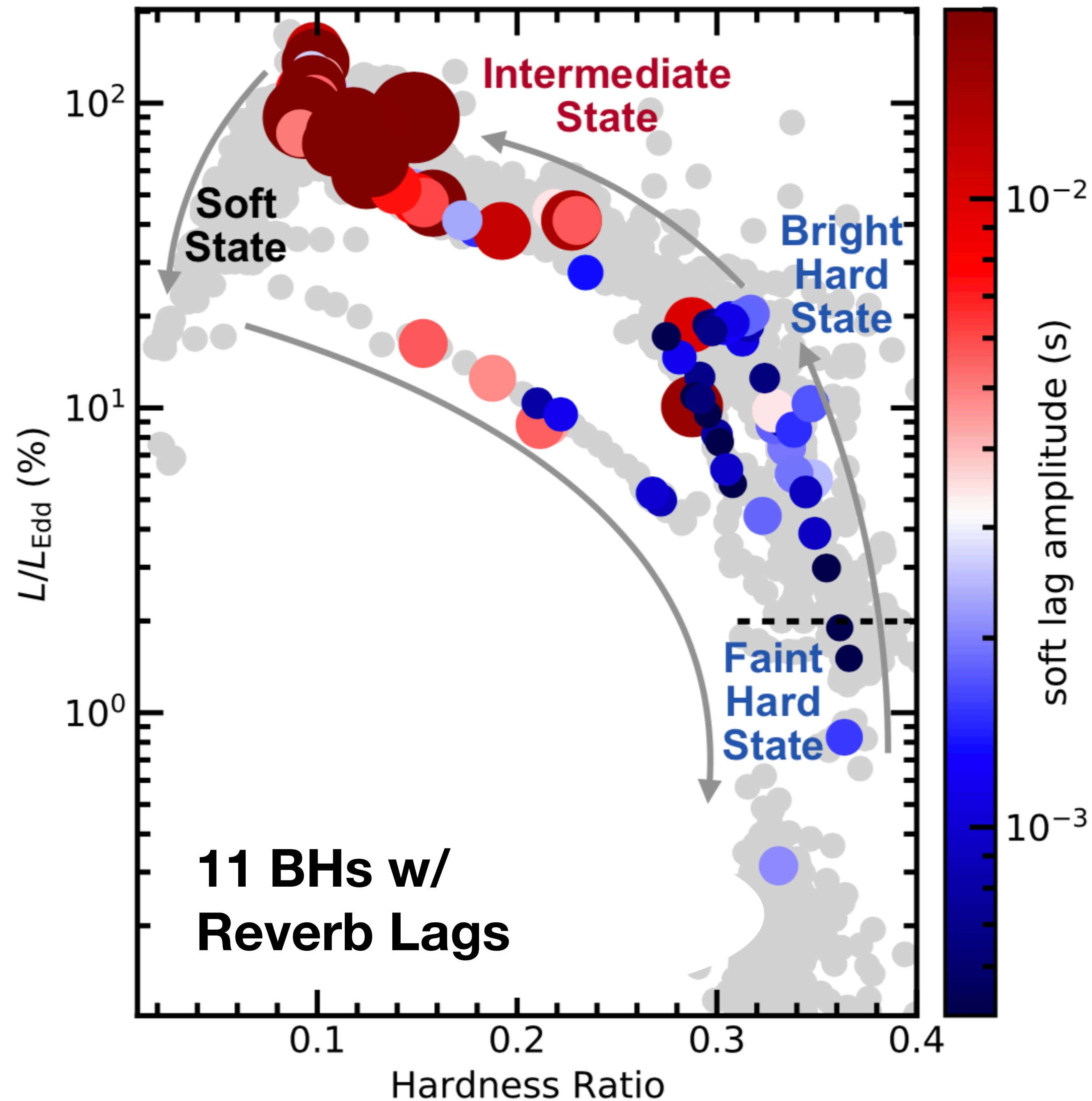
10-40x more sensitive
than Chandra

low background



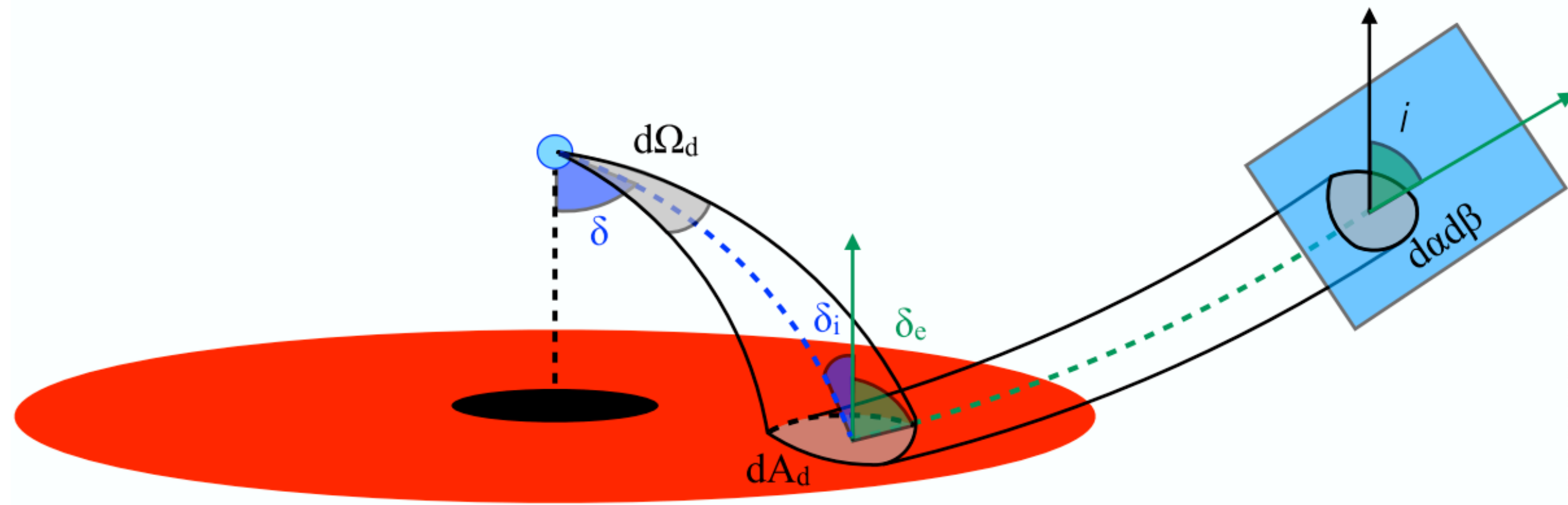
The NICER “Reverb Machine”

Wang, Kara+22

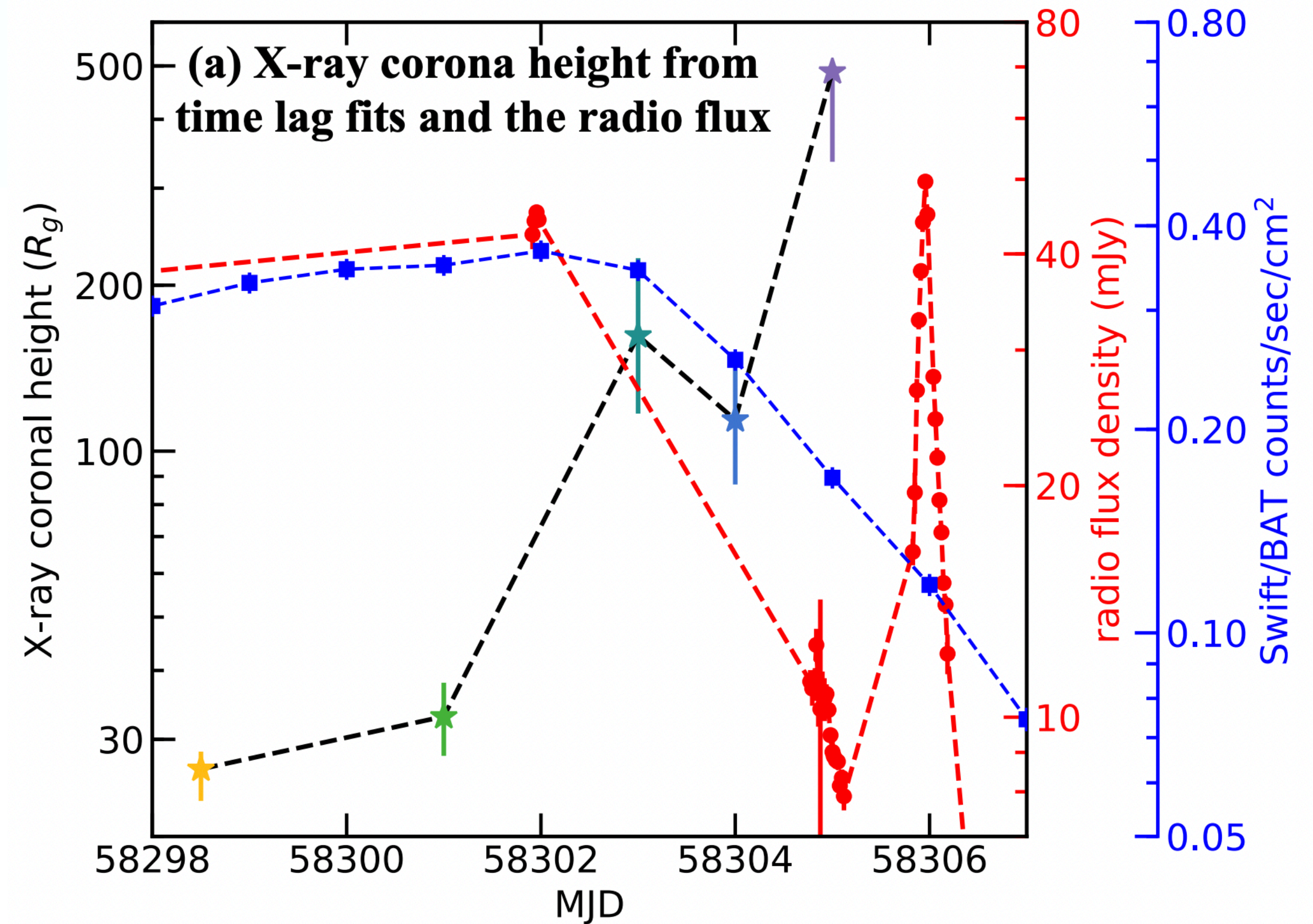
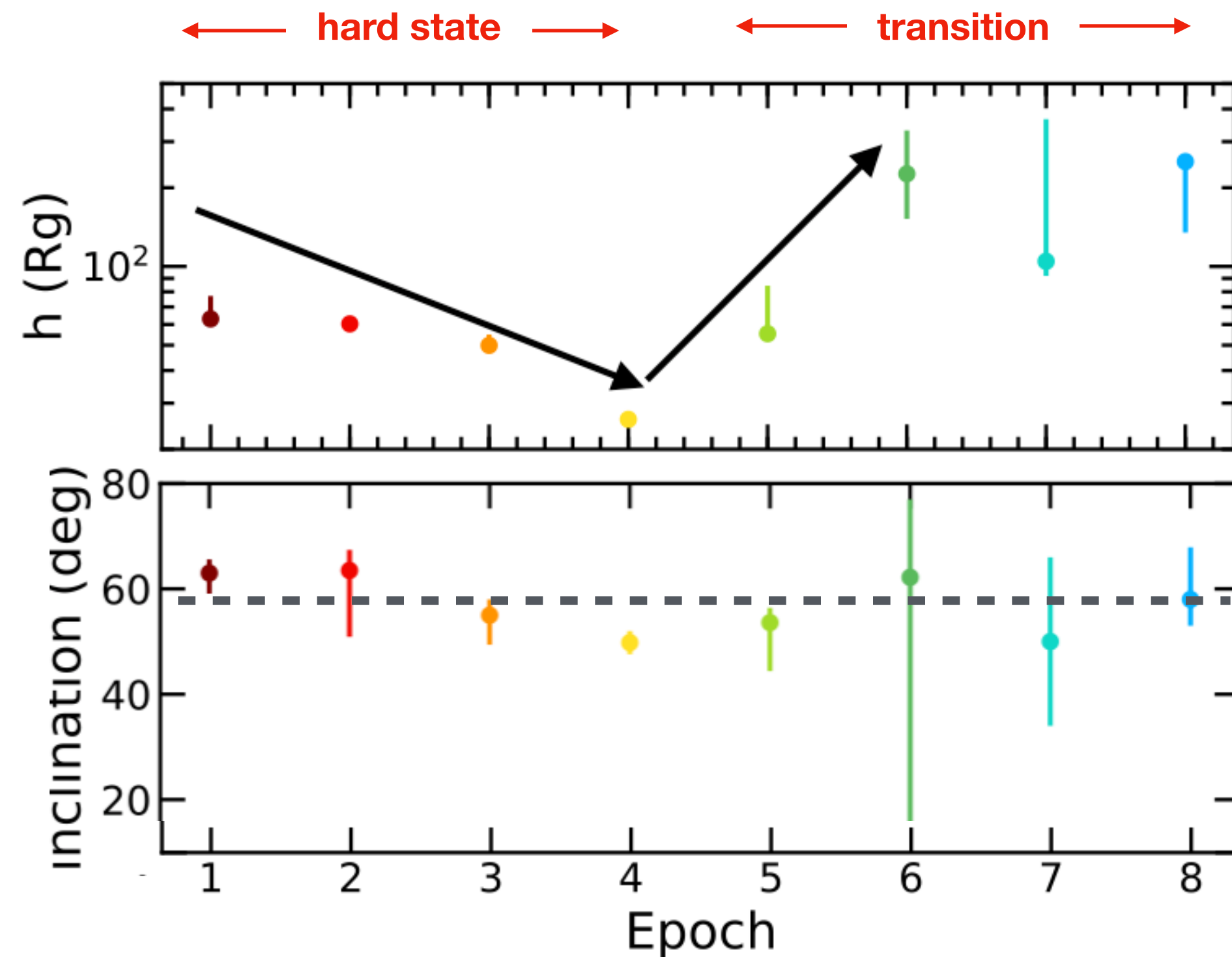


Jingyi Wang, MIT
5th Year PhD Candidate
NASA FINNEST Scholar

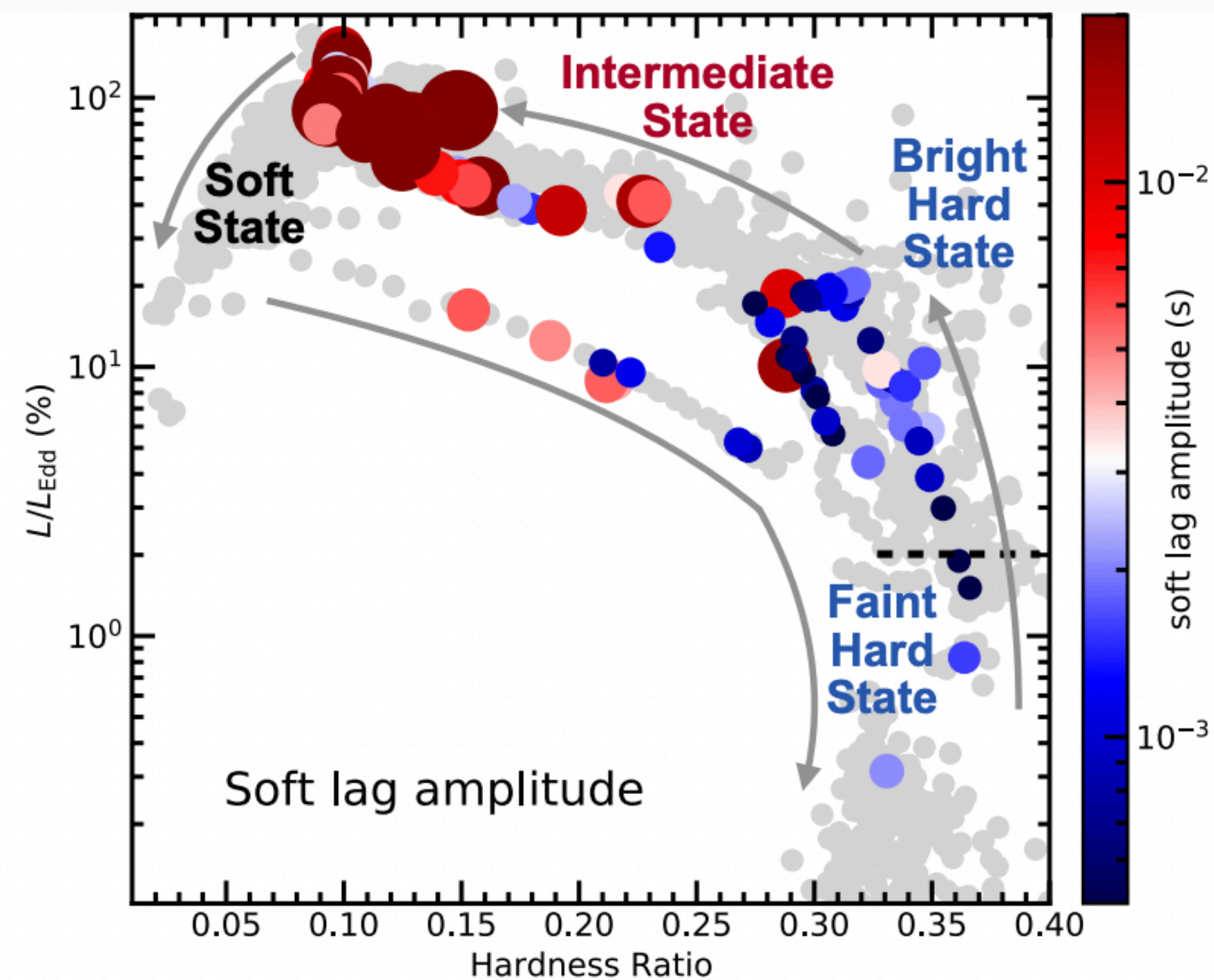
Modeling the lags



Ingram+19
Mastroserio+20



Wang, Mastroserio, Kara et al., 2021

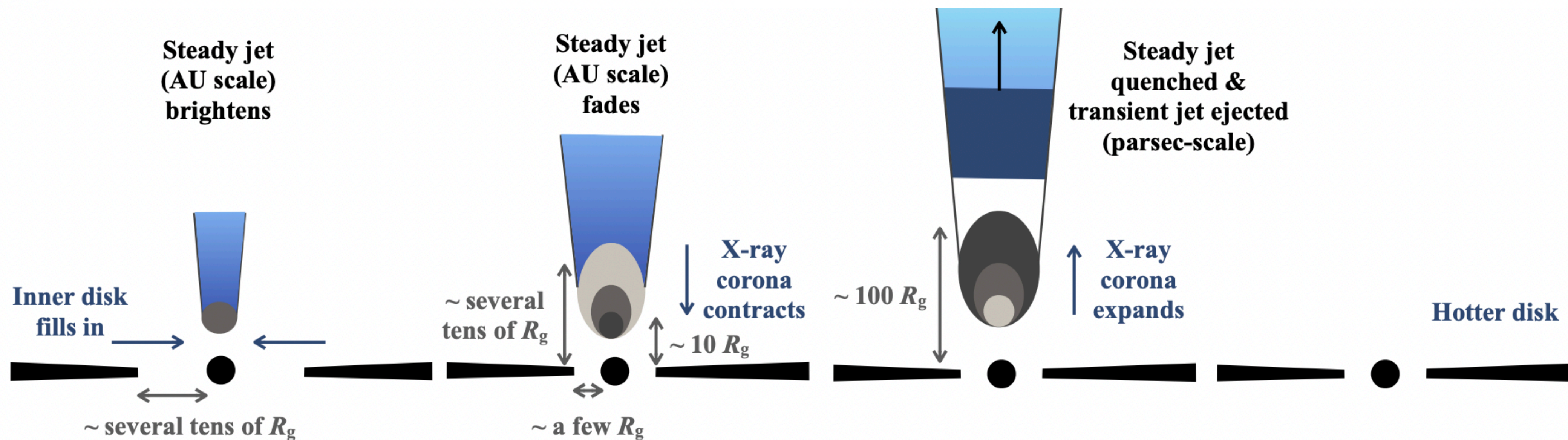


Faint Hard State
 $< 1\text{--}2\% L_{\text{Edd}}$

Bright Hard State
 $> 4\% L_{\text{Edd}}$

Intermediate State

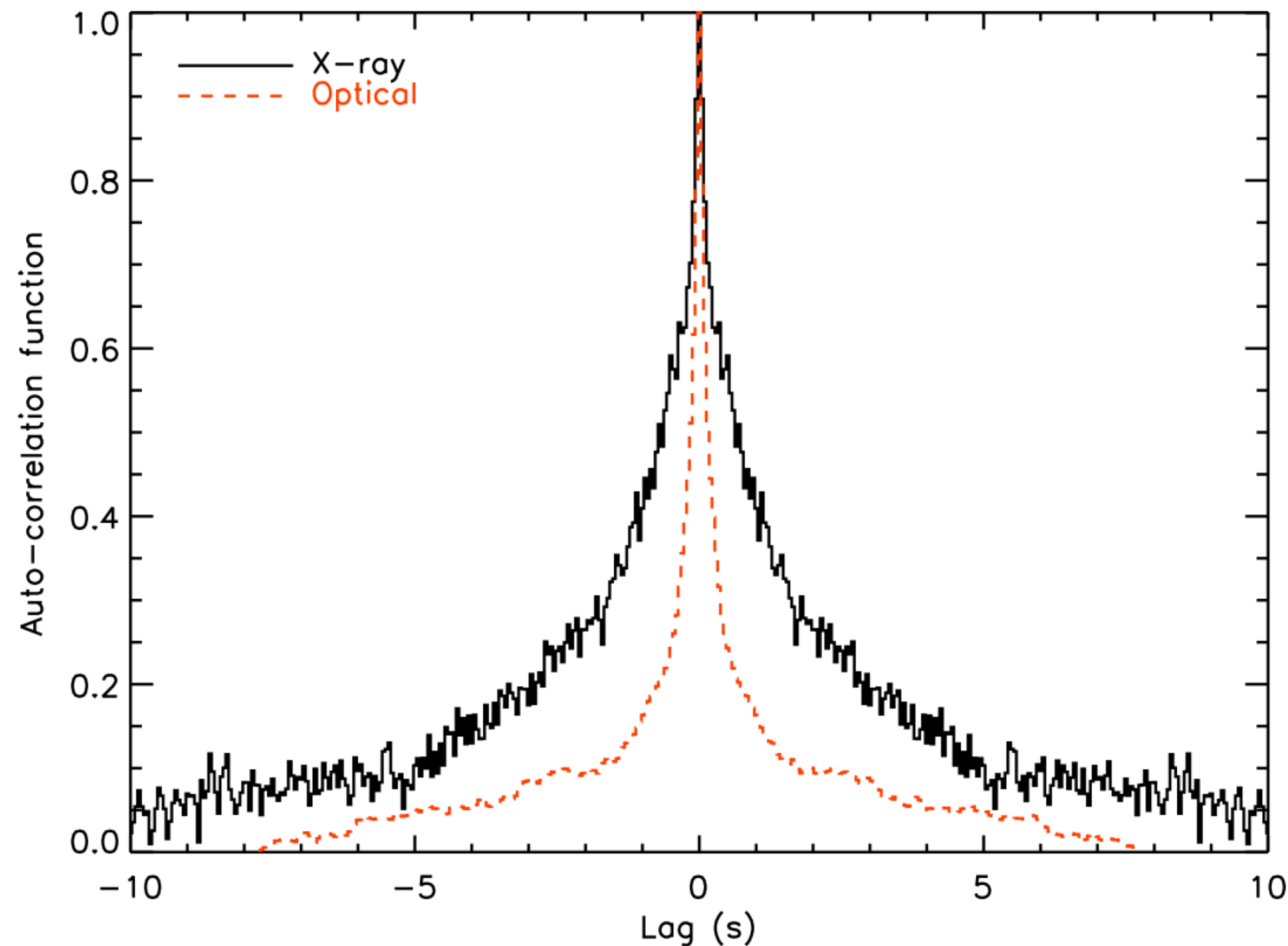
Soft State



Connecting the corona and the jet

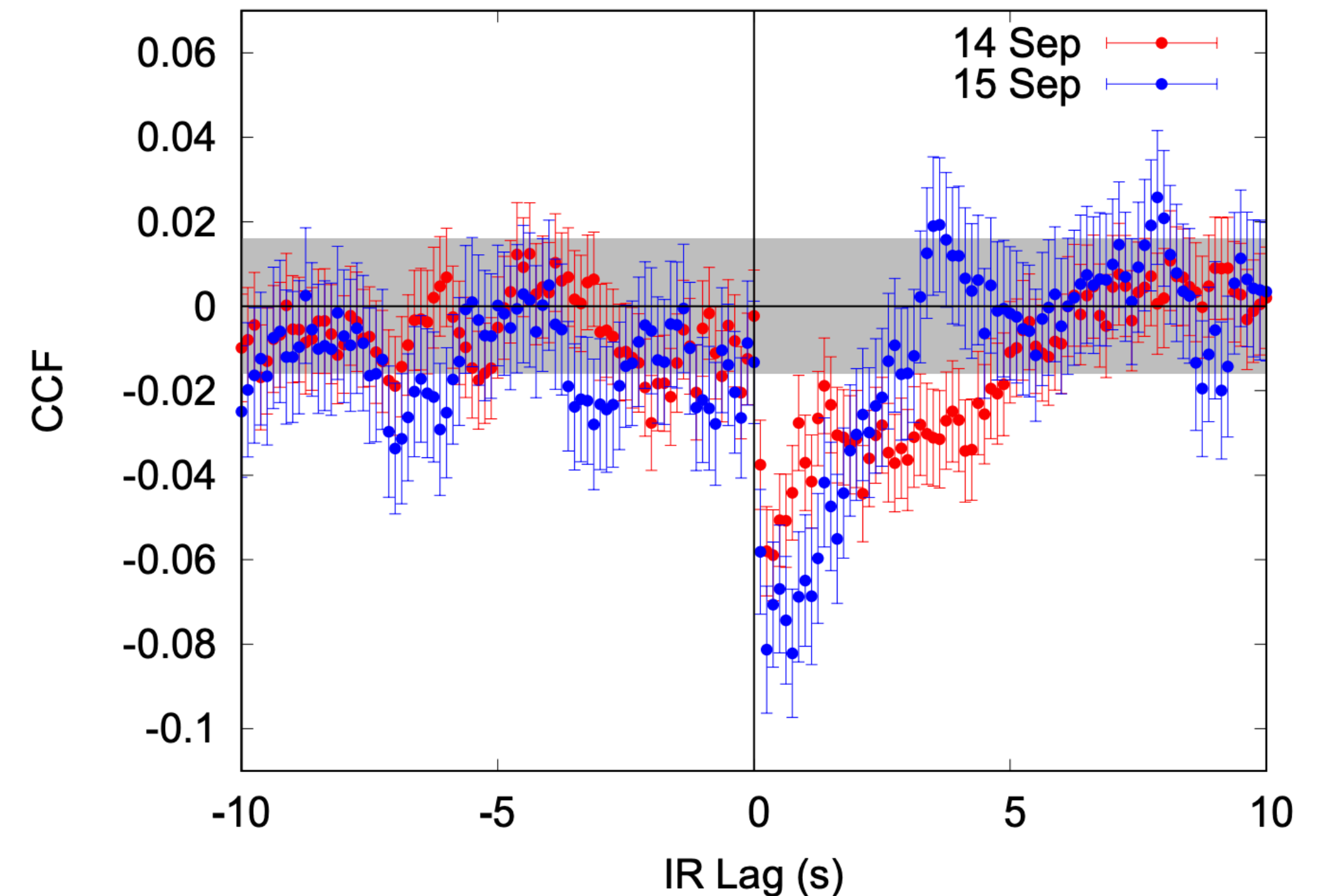
X-ray/IR timing studies

Gandhi et al., 2008



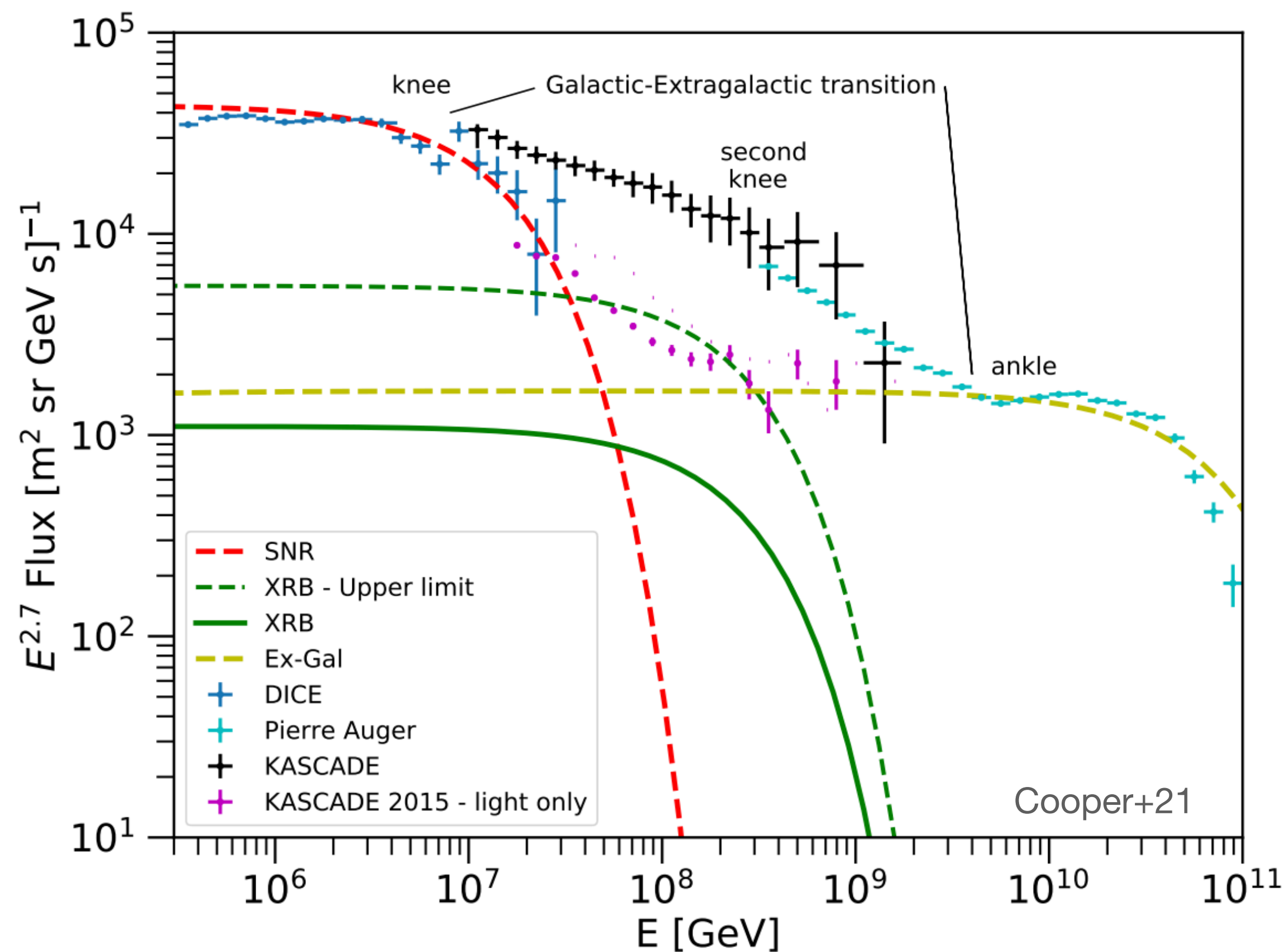
Optical ACF narrower than X-ray
Disfavors reprocessing

Vincentelli et al., 2019



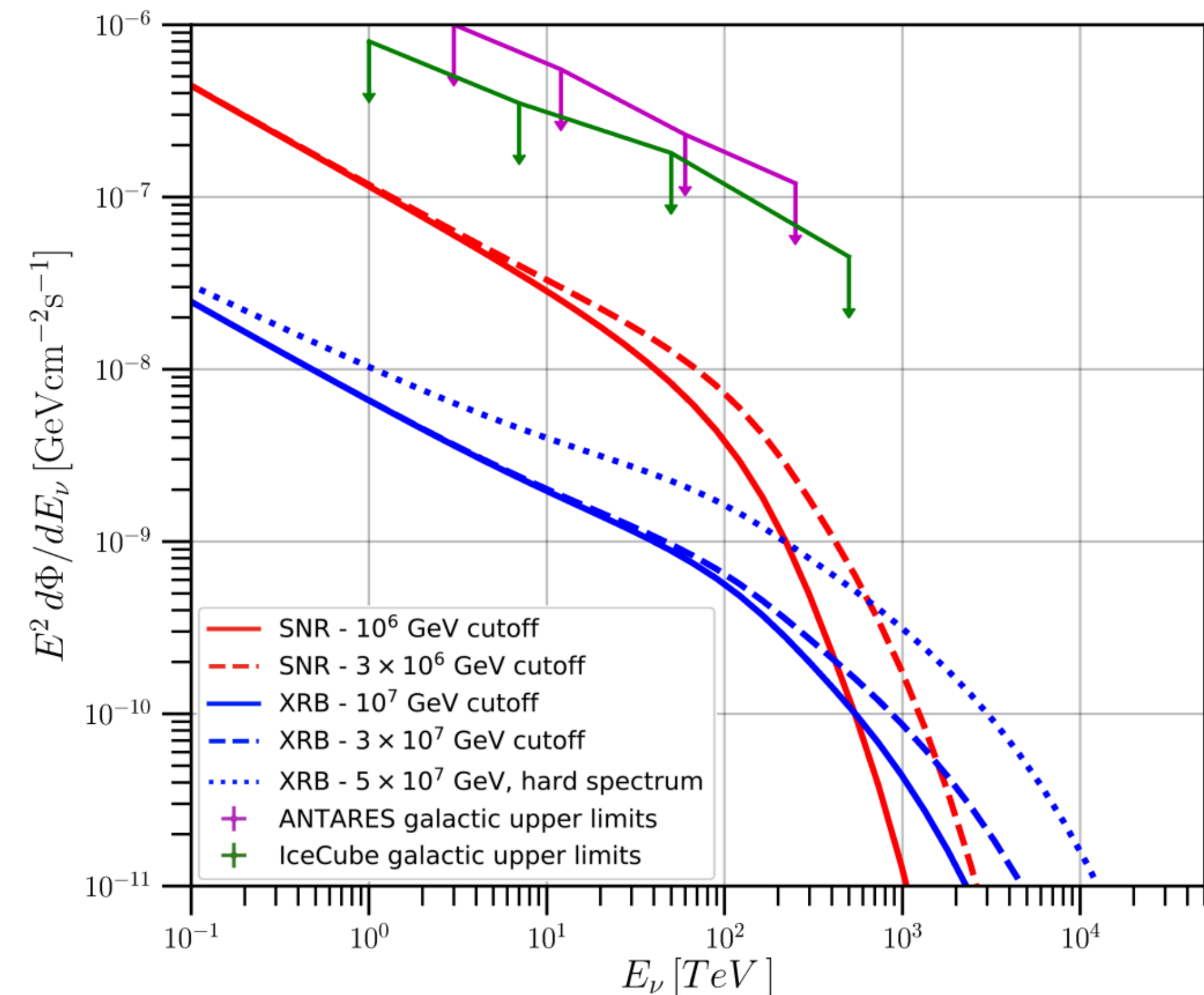
Optical/IR lags X-rays by 0.1s
Internal Shock Model? (Malzac+13)

Black Hole Transients (scaled down AGN) as Cosmic Ray Emitters



Shocks propagating in black hole XRB jet can accelerate charged particles to very high energies

Could explain Galactic 'knee' of CR spectrum?



Neutrinos also expected from CR interactions with protons or photons

IceCube-Gen2 will probe 10x more volume

KM3-NET: Error circle of $< 0.1^\circ$ at PeV energies

What time-domain/multi-wavelength observations are critical for answering fundamental science questions for this source?

Fast follow-up of individual, bright black hole transients

- 1) High-cadence, high throughput X-ray observations
 - to measure black hole mass, spin and disk/corona geometry
- 2) Coordinated IR and Radio Observations with fast photometry
 - to measure disk/corona/jet causal connection
- 3) Coordination with next generation neutrino and TeV gamma-ray facilities
 - to measure particle content of jet

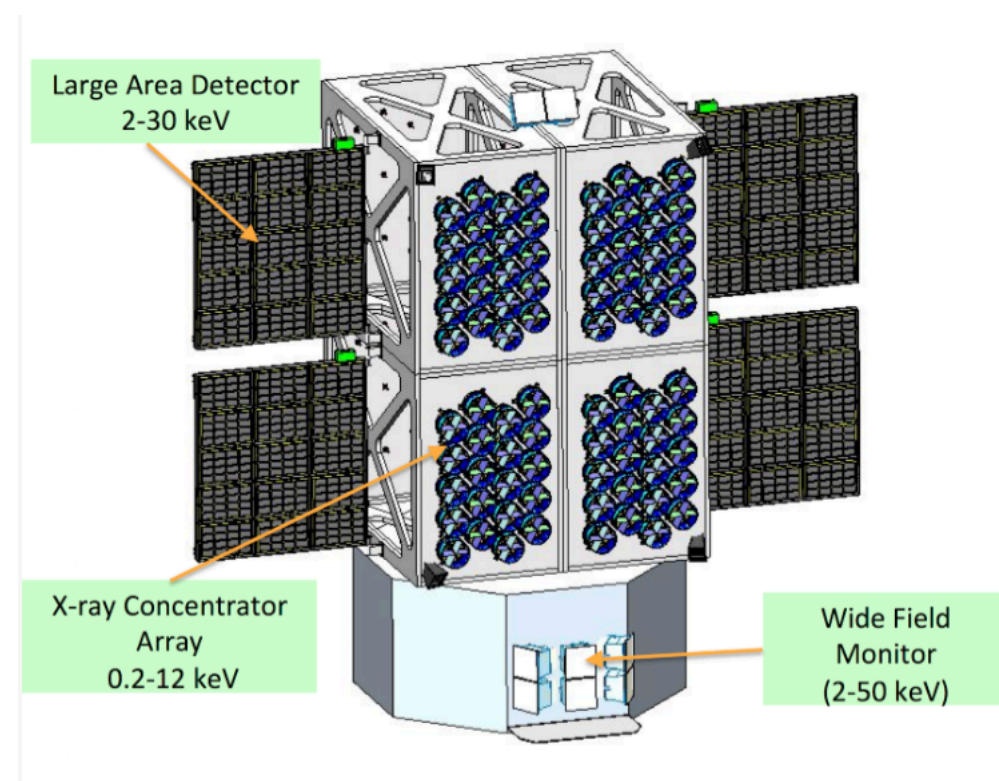
X-ray Binary Demographics

- 1) Cadenced, sensitive X-ray surveys of the Galactic Plane
 - Spectra can distinguish NS/BHs from CVs
 - Variability distinguishes MSPs from quiescent black holes
- 2) Correlate with next-generation neutrino observatories with good spatial resolution
- 3) Aid in identifying LISA continuous gravitational wave sources

What is needed for the time domain/multi-wavelength and/or multi-messenger detections described above (more theory work, more observations, new technology, new missions/facilities, etc.)?

Fast follow-up of individual, bright black hole transients

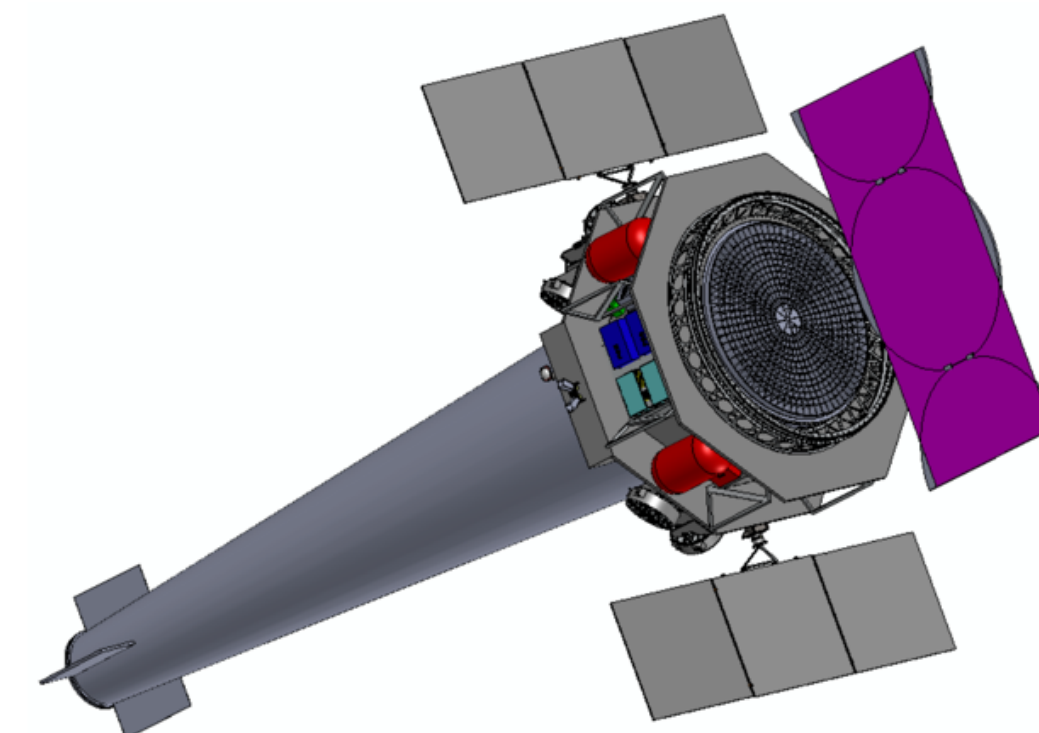
STROBE-X



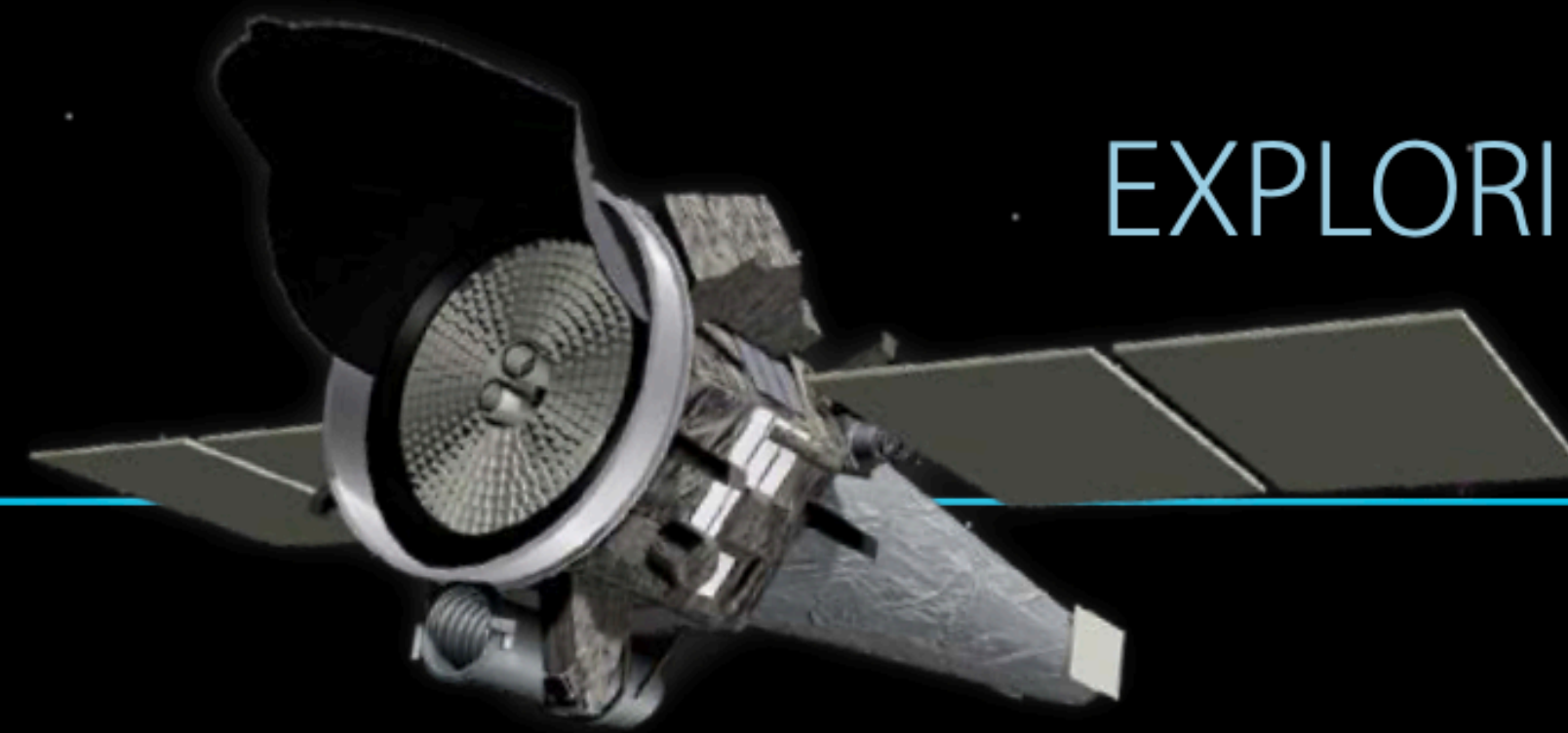
See PI Paul Ray!

X-ray Binary Demographics

AXIS
Advanced X-ray Imaging Satellite



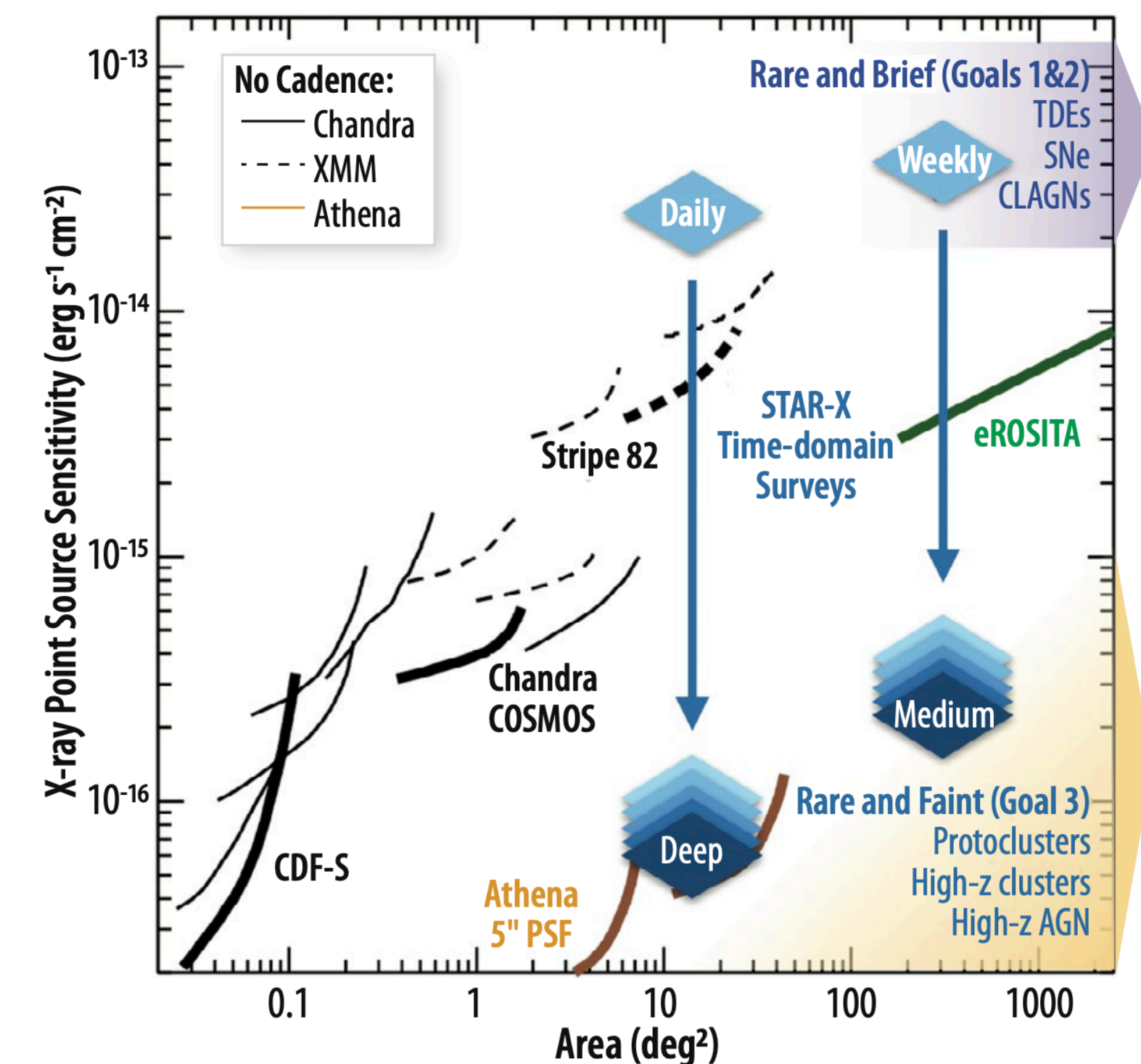
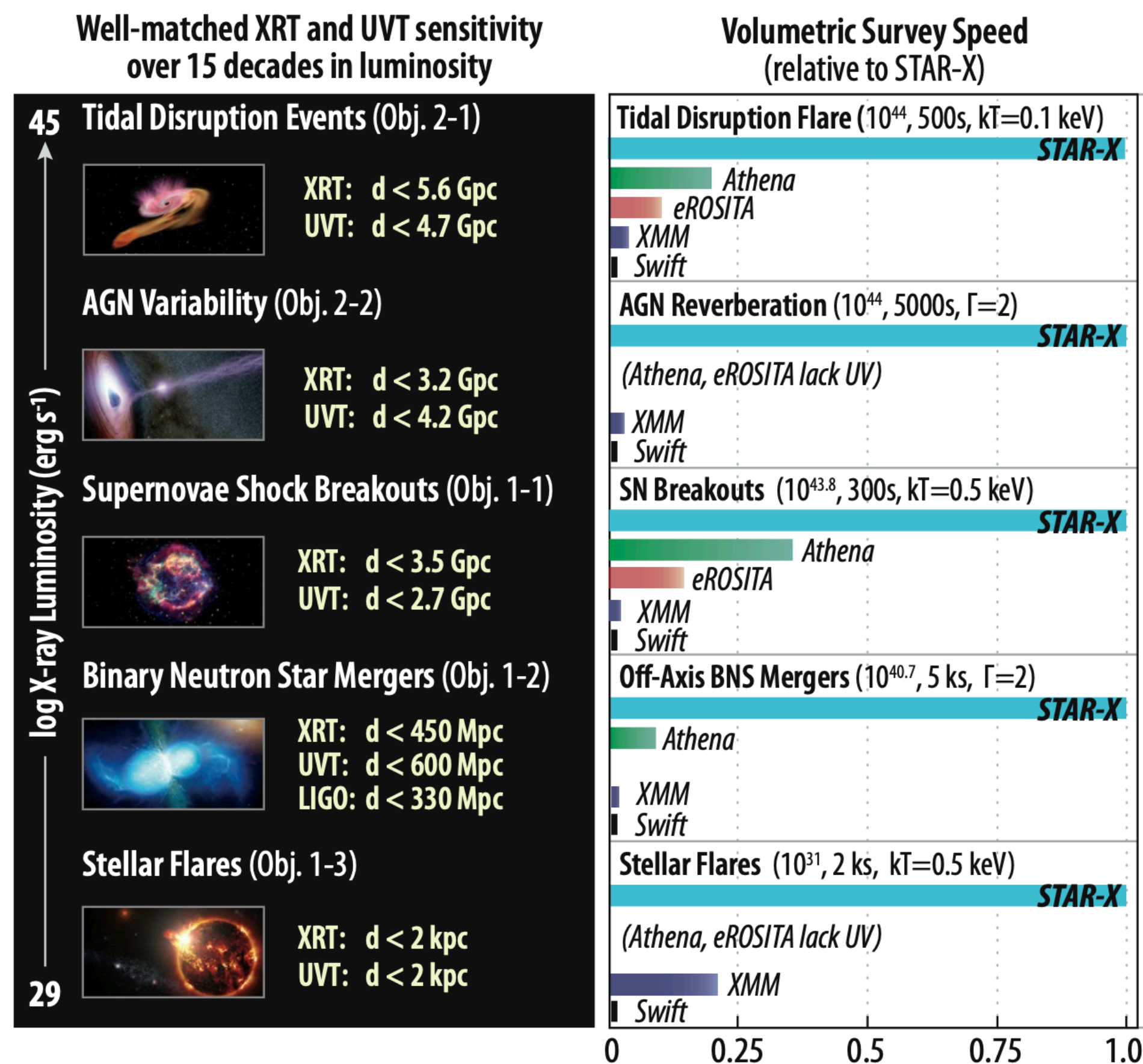
Survey and Time-domain Astrophysical Research eXplorer



EXPLORING THE FAST, FURIOUS, and FORMING UNIVERSE

PI: Dr. William W. Zhang, NASA's GSFC
DPI: Dr. Ann Hornschemeier, NASA's GSFC

What is STAR-X?: X-ray Telescope + UV Telescope + Rapidly-Responding Spacecraft



Selected for Phase A Study Last week!
Visit: <https://asd.gsfc.nasa.gov/star-x>